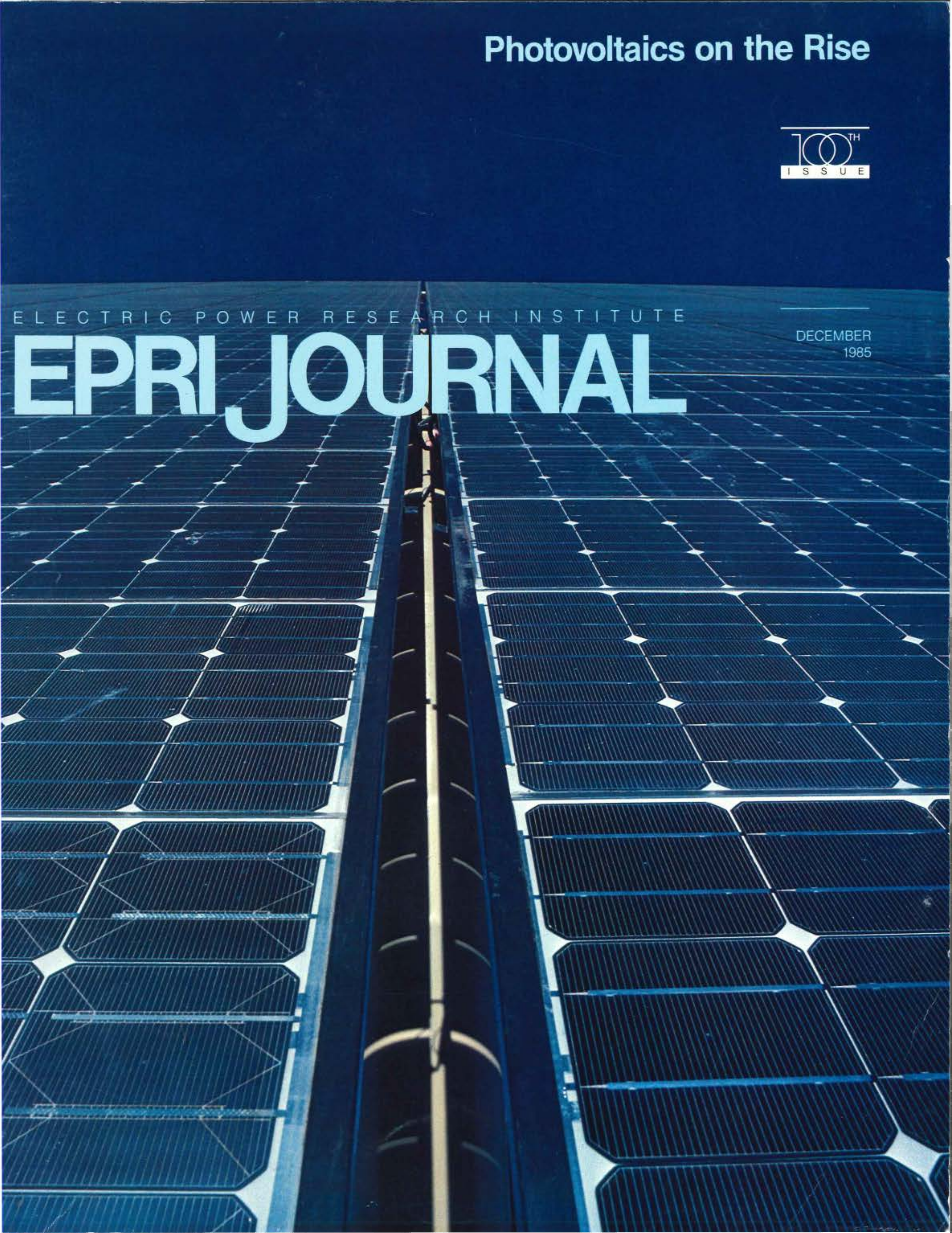
# Photovoltaics on the Rise

100TH ISSUE

ELECTRIC POWER RESEARCH INSTITUTE

# EPRI JOURNAL

DECEMBER 1985



EPRI JOURNAL is published monthly, with the exception of combined issues in January/February and July/August, by the Electric Power Research Institute. The April issue is the EPRI *Annual Report.*

EPRI was founded in 1972 by the nation's electric utilities to develop and manage a technology program for improving electric power production, distribution, and utilization.

EPRI JOURNAL Staff and Contributors
Brent Barker, Editor in Chief
David Dietrich, Managing Editor
Ralph Whitaker, Feature Editor
Taylor Moore, Senior Feature Writer
Michael Shepard, Feature Writer
Pauline Burnett, Technical Editor
Mary Ann Garneau-Hoxsie, Production Editor
Jim Norris, Illustrator
Jean Smith, Program Secretary
Christine Lawrence (Washington)
Kathy Kaufman (Technology Transfer)

Richard G. Claeys, Director
Communications Division

Graphics Consultant: Frank A. Rodriquez



Address correspondence to:
Editor in Chief
EPRI JOURNAL
Electric Power Research Institute
P.O. Box 10412
Palo Alto, California 94303

Cover: Photovoltaic cells convert sunlight directly into electricity at Arco Solar's 6-MW central station on the Carrisa Plains in California. This and other megawatt-scale PV plants now operating have bolstered confidence in the solid-state solar option as a future utility peak generating technology.

EPRI JOURNAL

Volume 10, Number 10 December 1985

100TH ISSUE

# Solar Cells: What a Difference a Decade Makes

Ten years is an interval of time we often use to assess the rate and shape of change on many levels—in our lives, in our national history, and in economics, as well as in the process of technologic evolution. So, in this one-hundredth issue of the *EPRI Journal,* we return to the topic featured in its first issue a decade ago and survey the course of change that photovoltaic (PV) cells have taken. In retrospect, the technology is one for which there have always been high hopes. But now a growing element of confidence also marks the outlook.

When the *EPRI Journal* first came on the scene, solar cells seemed quite a long shot for generating significant amounts of electric power, despite their by-then wide use in spacecraft. High materials and manufacturing costs, coupled with low conversion efficiencies, made photovoltaics appear a distant contender behind thermal conversion concepts in a race among solar alternatives to compete with fossil-fuel-based generation.

But what a difference a decade makes. Today, photovoltaics has emerged as a front-running renewable energy technology against a 10-year backdrop of rapidly rising (but now softening) oil prices and intensive (but now subdued) government-sponsored R&D in advanced energy systems. Indeed, federal R&D attention on photovoltaics has been a key factor in the technology's evolution from milliwatt space power modules to the megawatt-scale field installations now operating in California.

In the last few years, however, the R&D ball has been largely passed from the government to the private sector. Industrial involvement in photovoltaics, particularly by major oil companies, is maintaining momentum in the steady march to commercial competitiveness in such selected markets as remote power and in a widening range of consumer products. But the PV industry remains a fragile one. To continue to mature, it must further develop near-term markets for PV products, both here and abroad, to sustain the necessary corporate commitment to technology development.

As the PV industry and technology continue to approach economic viability in the ultimate market—that of bulk power generation—EPRI and its electric utility sponsors can take pride in having had a significant impact on the course of development over the past decade by striving continually for high sunlight-to-electricity conversion efficiencies. EPRI's work with scientists at Stanford University, begun in 1976 amid a flurry of research interest in numerous PV approaches, has, for one major PV option, succeeded in achieving the high conversion efficiencies that we knew were needed for utility applications but that were then seen as extremely ambitious. We are increasingly optimistic that within the next decade, high-concentration solar cell technology will be available for utilities in the nation's southwestern Sunbelt to begin generating significant amounts of economic and reliable power. Flat-plate PV technologies are also showing impressive efficiency improvements that bode well for their early introduction in bulk power markets over the same period.

In addition to the technical and cost improvements that have been achieved with photovoltaics in the last 10 years, a perceptible shift in the outlook of utilities toward the technology is also apparent. Skepticism is giving way to an earnest desire for hands-on experience with PV systems as many utilities recognize the technology's promise as a future generating option. A number of utilities have become substantially involved through their own testing and evaluation programs or through intimate participation in research programs with PV developers.

Such interest reflects a growing recognition of PV technology's innate advantages as a potential generating option. Its modular nature is appealing both in terms of adding new capacity incrementally and quickly and in terms of the capital cost and financial risk of doing so. These advantages of modularity are being demonstrated convincingly by megawatt-scale installations operating today. The economies of modularity have also permitted EPRI to maintain critical research and testing efforts in photovoltaics at relatively modest funding levels. We expect these economies to be equally important to the advent of the technology's commercial introduction and use.

Although we are optimistic about the prospects of photovoltaics as a future utility generating option, we recognize that development of this ultimate market for solar cells will not happen overnight. Thus it is essential that near-term markets continue to be developed and that fundamental research aimed at pushing the technology to its physical limits of efficiency and reliability be sustained. This latter goal implies more than an empirical approach to R&D; it demands a long-term commitment to improved understanding of the physics and materials science of photovoltaics. To achieve these goals, we must also acknowledge that PV R&D is a truly international undertaking and that we will benefit from expanded international exchange of information and scientific understanding.

The key lesson of this past decade is to set our sights high and then strive for high performance with both focus and patience. If the PV community can continue this approach and if nature continues to cooperate, then the next decade may make an even larger difference: the introduction of photovoltaics as a truly competitive source of bulk electric power worldwide.

Edgar A. DeMeo

Edgar A. DeMeo, Manager
Solar Power Systems Program
Advanced Power Systems Division

# Authors and Articles

## To Our Readers

We want you to join us in celebrating the publication of the 100th issue of the *EPRI Journal*. A magazine like this could not exist without the loyal support and attention of its readers, and we consider you the best of audiences.

Many of you have been with us for years. You have helped to make the communication two-way, helping to shape and guide the *Journal* through its evolution during the first 10 years. The *Journal* staff would like to thank you for your interest and contributions.

We have enjoyed producing this chronicle of change and progress, and we hope you continue to find this service of value.

From left to right: Barker, Dietrich, Shepard, Norris, Garneau-Hoxsie, Rodriquez, Moore, Smith, Whitaker, Burnett.

Photovoltaic energy systems may yet become an important part of the electric utility generation mix. This month's lead article, **Photovoltaics: Pioneering the Solid-State Power Plant** (page 6), reports on sustained R&D progress toward solar cells that are efficient, affordable, and reliable at utility scale. The author is Taylor Moore, the *Journal*'s senior feature writer, who received technical guidance from three research managers in EPRI's Advanced Power Systems Division.

Edgar DeMeo, manager of the Solar Power Systems Program, has been responsible for EPRI research in photovoltaic, solar-thermal, wind, and biomass energy technologies since January 1980. He joined the Institute as a project manager in August 1976 after six years on the engineering research faculty at Brown University; before that he was an instructor at the U.S. Naval Academy for two years.

Roger Taylor, a project manager for photovoltaic energy R&D since July 1980, was formerly with the Solar Energy Research Institute for two years, where he was mainly concerned with electric utility applications of solar technologies. Between 1976 and 1978 he was a research analyst with Arizona Public Service Co.

John Crowley, also a project manager, is particularly concerned with photovoltaic thin-film technology. He came to EPRI in December 1983 after eight years with Lockheed Missiles & Space Co., Inc., as a staff scientist for investigations of thin films, silicon device processing, and radiation effects. Earlier, Crowley was a research associate at the Stanford University Center for Materials Research.

Recognizing that R&D can be a tool for solving near-term problems, electric utility engineers are turning to EPRI on a one-to-one basis. **Technology Transfer One-to-One** (page 20) documents several cases from the recent experience of EPRI's Coal Combustion Systems Division. In writing the article, the *Journal*'s feature editor, Ralph Whitaker, conferred with several EPRI and utility staff members—especially EPRI's Rolf Manfred.

Manfred, a subprogram manager in the Fuel Quality Program, took on added responsibility in 1985 when he was named senior technical manager for the Fossil Fuel Power Plants Department. He now coordinates technology transfer matters, including his division's increasing member contacts on specific R&D applications. Manfred came to EPRI in November 1979 after four years with Acurex Corp. as manager of energy systems programs. Earlier, he was with Aerojet Solid Propulsion Co. for 18 years, where he became director of advanced technology.

■

Because fuel rods from nuclear power reactors in the United States are not recycled (reprocessed) to recover still-fissionable material, fuel-cycle economy calls for measures to get more energy from each rod. **Designing Fuel Rods for High Burnup** (page 28) reviews R&D to extend the productive life of fuel rods without their suffering adverse thermal, chemical, or mechanical effects from their own radiation in a reactor core. Science writer John Douglas developed the article with the assistance of two staff members of EPRI's Nuclear Power Division.

David Franklin is manager of the LWR Fuels and Spent-Fuel Storage Program, which was established in September of this year. He joined EPRI in August 1976 and became a program manager for core materials in June 1980. Franklin was previously with Combustion Engineering, Inc., for three years, where he became the supervisor for cladding development. From 1969 to 1972 he was at Argonne National Laboratory, eventually as manager of fuel manufacturing.

Joseph Santucci is a project manager specializing in core materials. He joined EPRI in December 1982 after four years as a project engineer for S. M. Stoller Corp., consulting with utilities on nuclear fuel cycle problems. Earlier, he was a nuclear analyst on the Clinch River breeder reactor project for Burns and Roe, Inc.

■

Competing demands on water resources, plus the growing demand for electric power in dry regions, are making a case for power plant cooling processes and equipment that use less water. **The Dry Look in Cooling Towers** (page 34) provides an update on technology that has been under EPRI-sponsored development and field testing for several years. The article is by Joel Shurkin, science writer, in cooperation with two staff members of EPRI's Coal Combustion Systems Division.

John Bartz, whose R&D specialty is heat rejection equipment and processes, has been with EPRI since July 1978. He was formerly a program manager for three years with the Linde Division of Union Carbide Corp., where much of his work involved an ammonia-based cooling cycle. Bartz was earlier a research engineer with Calspan Corp. (formerly Cornell Aeronautical Laboratory, Inc.) for 13 years, much of that time in fluid mechanics research.

John Maulbetsch has been the manager of EPRI's Air Quality Control Program since October 1984; before that he was manager of the Heat, Waste, and Water Management Program for eight years. He came to EPRI as a project manager in August 1975 after seven years with Dynatech Corp., where he directed energy research and consulting for Dynatech's R&D subsidiary. Still earlier, he was an assistant professor of mechanical engineering at the Massachusetts Institute of Technology.

Taylor DeMeo Crowley

Manfred

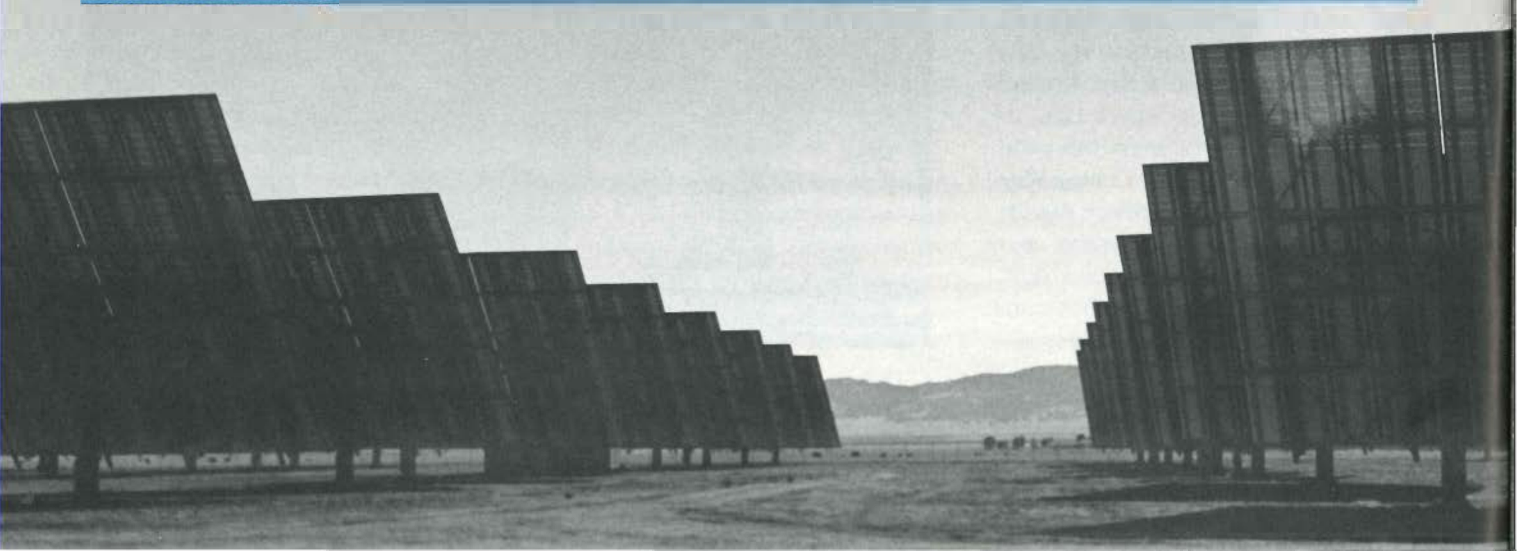
Santucci Franklin

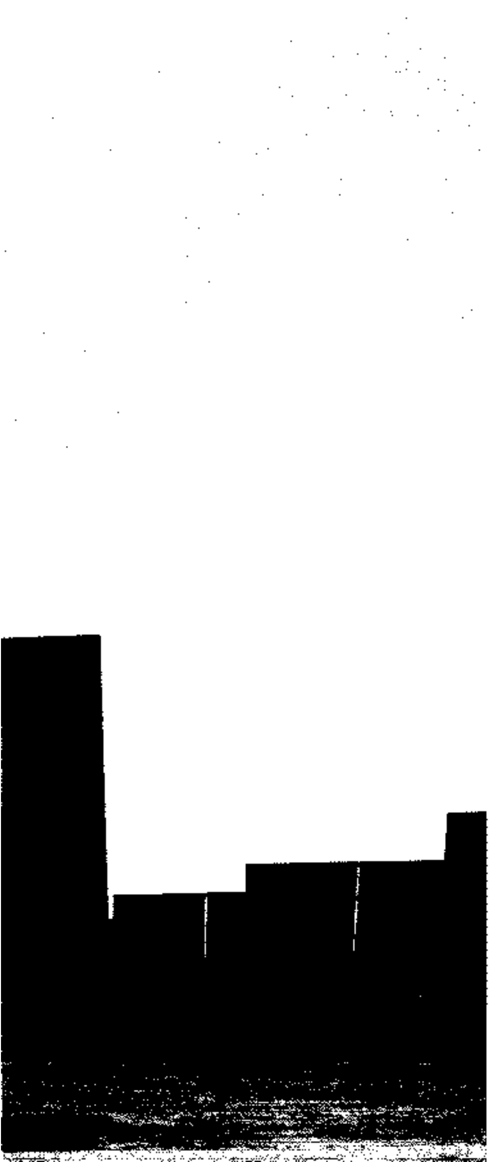
Bartz Maulbetsch

Photovoltaics

# PIONEERING THE SOLID-STATE POWER PLANT

Steady R&D advances toward high-efficiency, low-cost solar cells point to a bright future for utility applications of photovoltaics.





Semiconductors have truly wrought a revolution in the technology for processing and communicating information. Computers and their tiny integrated circuits-on-a-chip have reduced much clerical and calculation drudgery to the blink of an eye, and their lightning speed has made possible global communications of a dimension unimaginable a few decades ago. But the age of silicon remains in full swing; its technologic marvels are still emerging. One of these is the photovoltaic (PV) cell—made of thin layers of silicon or other semiconductor materials that convert sunlight directly into electricity—a device that by the end of this century, researchers believe, could begin to make a significant contribution to the energy supply in this country, as well as in other parts of the world.

Of all the renewable energy technologies that have been the focus of sustained government and private R&D efforts in the last two decades, perhaps none has so captured the public's fascination or such a share of research investment as photovoltaics. From its early development as an exotic power source for spacecraft, photovoltaics has endured as the leading high-technology solar option that promises to supplement the world's declining long-term stocks of fossil fuels for generating electricity and to bring electric power to areas and developing countries now without it.

Indeed, a growing industry with revenues of $130 million a year now exists worldwide, producing hundreds of thousands of low-efficiency solar cells for use in dozens of such consumer products as calculators, watches, and battery chargers; in more-sophisticated applications, including radio transmitters and repeaters, navigation aids, and cathodic protection from corrosion for wells and pipelines; and in a broad range of remote power applications here and abroad, including irrigation pumps, isolated villages and clinics, and desalination plants. The more than 20 makers of PV modules in the United States shipped products totaling some 8.4 MW of peak-rated capacity in 1984 alone.

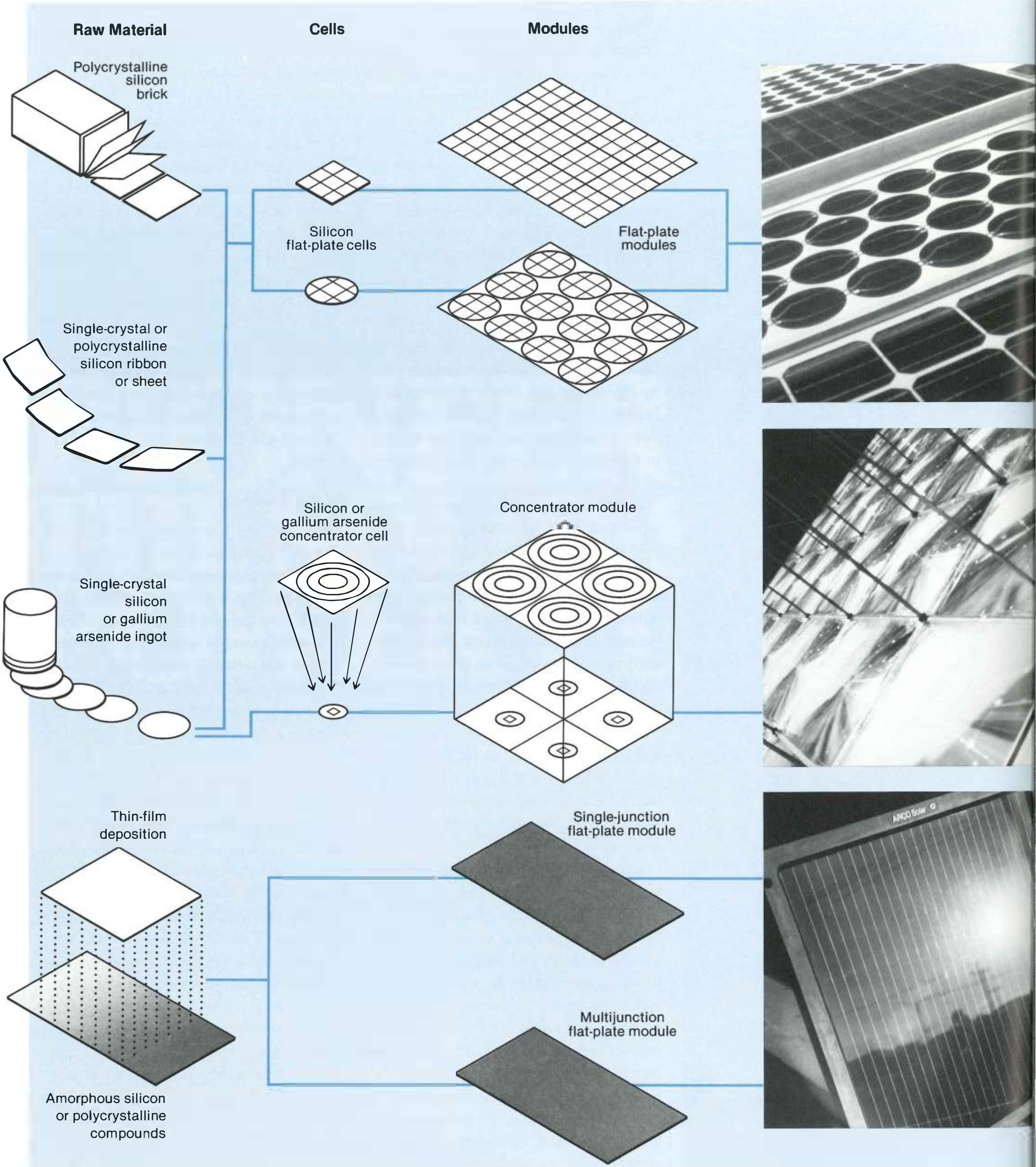
Although these uses and initial markets for photovoltaics have been important in demonstrating the technology's feasibility and environmental advantages, as well as in spawning a fledgling cell manufacturing industry, its ultimate promise has long been seen as a source of utility-scale bulk electric power generation. Most experts continue to believe that if PV power is to make a significant contribution to the energy supply in the industrialized nations, it must be at a price that competes with conventional generating technologies that use coal, oil, and uranium.

**Bright prospects**

Until recently the prospects for realizing this potential remained unclear, despite continuing R&D progress and the infusion of an estimated $1.5 billion in public and private funds since 1976 for research aimed at increasing the energy conversion efficiency of cells and reducing their manufacturing cost. Over the past decade the attention given to PV R&D by the federal energy program has been the single most important element in raising the technology's visibility and in launching industrial development.

In recent years the federal R&D program in photovoltaics has undergone significant changes in scope, focus, and funding. Continuation of tax credits that made the economic difference in some PV system installations is uncertain, and a strong U.S. dollar has helped dampen overseas markets for American manufacturers against aggressive foreign competitors. Moreover, photovoltaics has had to chase a moving target in the price of oil. Recent oil price declines threaten perceptions of when photovoltaics will actually compete with fossil-fuel-fired generation.

But the perseverance of the PV in-


Raw Material
Cells
Modules
Polycrystalline silicon brick
Silicon flat-plate cells
Flat-plate modules
Single-crystal or polycrystalline silicon ribbon or sheet
Silicon or gallium arsenide concentrator cell
Concentrator module
Single-crystal silicon or gallium arsenide ingot
Thin-film deposition
Single-junction flat-plate module
Multijunction flat-plate module
Amorphous silicon or polycrystalline compounds
ARCO Solar

## Photovoltaics: From Cells to Modules

**Conventional PV cells** are manufactured from silicon wafers sliced from crystal ingots or bricks. Such cells, though available commercially, are limited by low energy conversion efficiencies. Advanced manufacturing methods include the dendritic web, in which sheets or ribbons of silicon are withdrawn from molten feed. Higher efficiencies have been achieved, but the research challenge is to grow large-area ribbons at high rates while maintaining high efficiency.

**Concentrating solar cells** feature smaller cell area and higher efficiency than conventional cells. Optical concentration is provided by Fresnel lenses; these form the top cover of the assembled modules, which must closely track the sun to keep intense beams focused on the cells. EPRI is supporting R&D to determine whether concentrator cells can be mass-produced by using process techniques developed for integrated-circuit manufacturing.

**Thin-film PV devices** are produced by vapor or plasma deposition of amorphous silicon or other semiconductor materials on a glass substrate. These materials respond to a broader spectrum of solar radiation than do crystalline silicon devices. Multiple thin films or amorphous materials—each tailored to a specific part of the light spectrum—can be overlaid in a multijunction configuration. Single-junction thin-film modules are commercially available, but higher efficiencies, larger modules, and lower manufacturing costs are the aim of intensive worldwide research in this leading-edge PV technology.

dustry and the research community is beginning to pay off. Exciting new milestones in cell efficiency, cost reduction, and materials advances are being announced with increasing frequency; improved cell technology is moving from the laboratory to the production line; and several pioneering megawatt-scale PV plants are now generating reliable power on utility grids, providing essential field construction and operating experience and a realistic picture of current total system costs in addition to cell performance.

Moreover, several utilities are getting involved with the technology on a smaller scale, outfitting homes and test stands with solar cells to gain familiarity with what many feel may eventually become an economically viable, modular option for adding peak generating capacity. Some utilities are also closely involved with performance evaluations of PV field installations that range from several hundred kilowatts to several megawatts.

The cost of cells has fallen dramatically over the last 10–15 years, from roughly $100 per peak watt (Wp) of electric output to around $5/Wp if multicell modules are purchased in large quantity. But most experts agree cost must come even lower—to around $1/Wp—to economically rival conventional generation in the 1990s and beyond.

Although its success and future as a bulk power source are by no means assured, "the momentum is there and the technical progress and early field test experience point to a bright future for utility-scale applications of PV technology," says Edgar DeMeo, manager of the Solar Power Systems Program in EPRI's Advanced Power Systems (APS) Division. "Over the past several years, we've seen significant progress with several candidate PV technologies, continued promise for others farther out on the horizon, and very encouraging indications from megawatt-scale field tests."

Adds John Cummings, director of the Renewable Resource Systems Department in the APS division, "Recent achievements in cell development research and in new efforts to bring this technology to the manufacturing stage, coupled with successful central station PV projects in California, have increased our confidence that photovoltaics could be a viable generating option for utilities in the southwestern United States in the next decade."

Whether the economics and technology will evolve sufficiently to permit expanded geographic application to other areas of the country may depend on the success of intensive worldwide research into amorphous thin-film semiconductors—the next generation of PV materials beyond today's silicon crystals. Characterized as at a stage of development analogous to that of conventional solar cells 15 years ago, amorphous materials may require another decade of relentless, fundamental research before they can rival today's crystalline cells. Yet researchers are optimistic even on this score, pointing to the critical mass of R&D attention converging on amorphous materials and research insights identified in work on crystalline cells that may help light the path to success.

### Leading candidates

Two years ago EPRI research managers and their utility and PV industry advisers surveyed the development status of photovoltaics and the almost bewildering array of materials, devices, and configurations that have survived the last decade's R&D trials. They found three technologies that appear to have a better-than-even chance of meeting the levelized energy cost target of 6–7¢/kWh (in constant 1982 dollars) and 30-year reliability for utility applications in the 1990s. These are optical concentrating–tracking systems that use high-efficiency (26–28%) crystalline silicon cells; lower-efficiency (15–17%) cells for flat-plate arrays manufactured

## Development Prospects at a Glance

The results of a wide-ranging EPRI review of photovoltaic technology in 1983 are summarized in the table below. Reflecting the judgment of leading PV researchers and the views of managers in the PV industry, utilities, government agencies, independent consulting firms, universities, and EPRI, the overview presents an assessment of various PV technologies based on probabilities of meeting specific cost and performance targets that could lead to widespread utility use of the technology. Three technologies were identified as meriting more aggressive research: high-concentration arrays, multijunction (tandem) amorphous silicon modules, and crystalline silicon sheet modules.

as sheets or ribbons of crystalline silicon; and (although at a much earlier stage of development than the previous two) amorphous silicon thin films (nominally 1 $\mu$m) used in tandem multijunction configurations designed to respond to the broadest spectrum of incident sunlight.

Utility cost and performance targets derived in studies by Roger Taylor, project manager for photovoltaics in the APS division, assume system installation in 1990 and cost levelization over the period 1990–2020. To meet the system cost target, assuming a Southwest site, flat-plate modules (of either crystalline or amorphous silicon) would have to cost no more than $150/m$^2$ and perform at 15% efficiency or better. Concentrating modules using more-efficient cells could cost more and still meet the target; $250/m$^2$ and 22% module efficiency (26% at the cell, allowing for optical losses) are the corresponding goals.

"There is reason to believe that the required efficiencies in both the flat-plate and concentrating-cell concepts can be achieved," says Taylor, "but there is more agreement in the industry about achievable performance with current PV technology than about achievable cost."

In a comparative analysis of the manufacturing steps and costs of producing each of the leading PV technologies conducted for EPRI this year, Research Triangle Institute, Inc., judged that further reductions in module costs to the $1–$2/Wp range would be possible for all the leading technologies (including conventional commercial cells) if key technical advances in certain manufacturing process parameters could be achieved. The analysis, avoiding predictions of when costs might reach the target levels, was based on an assumed annual production level of 25 MW or more for any one technology. But nearly all commercial PV plants today fall in the 1–5 MW/yr range of production capacity.

**Concentrating systems**

High-concentration (500×) PV systems that focus the sun's rays into intense beams on small-area (~1-cm$^2$) cells and track the sun for maximum exposure are emerging as the frontrunner for meeting utility requirements for near-term economic bulk power generation. But because the technology is not applicable to such near-term markets as consumer products and remote power, private R&D investment has been low. With the aim of reducing the remaining technical and business risks so that private industry involvement can increase if warranted, EPRI sponsors concentrating-silicon-cell PV technology research that began nearly 10 years ago with scientists at Stanford University.

Led by Richard Swanson, an associate professor of electrical engineering at Stanford, researchers have achieved steady improvement in cell efficiency and performance with a methodical approach that emphasized basic understanding of cell physics. With the help of a three-dimensional computer model of semiconductor device operation that allowed researchers to optimize performance factors, the team recorded 22.8% efficiency in quarter-scale (15-mm$^2$) laboratory cells at 500× geometric concentration. Cells operating at only 100× concentration have recorded efficiencies just over 25%.

"Swanson and his colleagues are closing in on the kind of cells we think are needed and can be made," comments Taylor. "Although there are still important technical issues to be resolved, the scientists at Stanford know where the remaining efficiency losses are, and they are continuing work to get around them. So we are beginning to make a transition from the laboratory to the process development phase." Some remaining development issues include reducing cell thickness by about one-third to around 100 $\mu$m, improving metallization of the electrical contacts on the back of the cell, and increasing the active cell area to 64 mm$^2$.

Tougher issues are posed by the impending transfer of research focus from the laboratory to the production floor. "First, we have to find out if the cell can be manufactured; then, if it can be produced as a complete package with a concentrating Fresnel lens and tracking system and meet the cost target of $250/m$^2$," explains Taylor.

A conceptual blueprint for the high-concentration PV array is already in hand. Black & Veatch Engineers-Architects led a team of contractors that recently designed a two-axis tracking 20-kW, 100-m$^2$ array to use the concentrator cell in a 100-MW ac central station application. The structural design is based on heliostat development experience in the federal solar-thermal central-receiver program. To focus the sunlight, Black & Veatch and Alliance Tool Co.'s Fresnel Optics Division are developing a new type of Fresnel lens in which the concentric facets are molded into a sheet of polymer that is directly bonded to glass sheet. Discussions are under way with other fabricators regarding the module's anodized aluminum secondary optical element and other components.

The next big step, will be to determine whether the concentrator cell can be manufactured in high volume and with consistent quality and efficiency. To find out, EPRI has contracted with Acrian, Inc., for process engineering directed at large-scale production of cells that could eventually reach hundreds of megawatts a year. The eight-year-old power electronics firm, based in California's Silicon Valley, has already had extensive experience with advanced production techniques for high-power integrated circuits.

EPRI and several utility cosponsors expect to spend some $10 million over the next three years on research, engineering, and equipment to demonstrate cell manufacturability at Acrian's San Jose, California, plant. "Once you know the cells can be manufactured and how to do it, gearing up for pro-

Within and even beyond the nation's Sunbelt, utilities are getting involved with photovoltaics, anticipating the technology's eventual cost-effectiveness in central station or distributed rooftop applications. A sample of the many emerging utility PV projects follows.

Massachusetts Electric Co., a subsidiary of the New England Electric System, has launched a $1 million R&D project with Mobil Solar Energy Corp. to install 2-kW PV arrays on 35 homes and commercial buildings in Gardner, Massachusetts, by mid 1986. Most of the solar panels will be connected to a single 13.8-kV distribution feeder for a two-year observation of transient response to voltage fluctuations on the feeder, the PV arrays, and their inverters, according to Donald Robinson, the utility's manager of energy conservation.

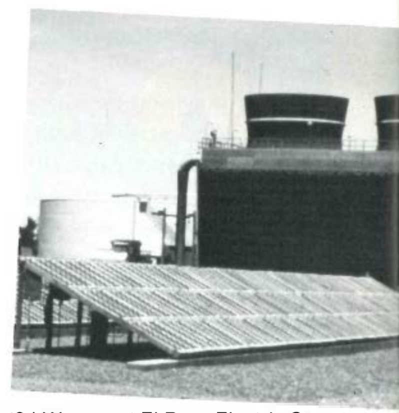
Also in New England, 24 PV modules totaling 4.3 kW are integrated with the roof of Boston Edison Co.'s innovative Impact 2000 house, a demonstration of the maximum use of solar and conservation measures.

At Virginia Power, a five-year PV test program is planned for a three-acre site beside the utility's North Anna nuclear station. Timothy Bernadowski, supervisor of energy assessments, says three 25-kW arrays could be operating by the end of this year. One features single-crystalline silicon flat-plate modules, and the remaining two arrays will use polycrystalline cells—one mounted as a fixed flat-plate and the other on eight low-profile tracking pedestals. Performance data acquisition and analysis will be provided by Sandia under a joint PV testing program funded by DOE and EPRI. After a year of baseline testing, the utility plans to vary the panels' tilt, tracking orientation, and other parameters for another four years of tests.

Boston Edison Co.'s PV-equipped Impact 2000 house

Concentrator array under test at PG&E

FP&L's 10-kW flat-plate array in Miami



18-kW array at El Paso Electric Co.

Farther south, Florida Power & Light Co. is monitoring a 10-kW flat-plate array mounted on a single-axis tracker at its Flagami substation in Miami. The array, specially designed by FP&L to withstand hurricane-force winds, was placed in service last June for five years of testing. Several PV modules, including panels mounted on four dual-axis trackers, are being evaluated at the Southeast Regional Experiment Station at Cape Canaveral, operated by the Florida Solar Energy Center.

The Southern Company is in the news with its announcement of a $7.2 million joint manufacturing venture with Chronar, a thin-film PV maker, and plans a grid-connected demonstration of single-junction amorphous solar cells by Alabama Power Co., its subsidiary. Plans call for the utility holding company's Southern Electric Investment Corp. to be the majority partner with Chronar in building a 1-MW/yr thin-film cell manufacturing plant, expected to be operating by the end of 1986 near Birmingham, Alabama. Meantime, on a site at Varnons, Alabama, Southern's Alabama Power has begun construction of a $1 million 100-kW demonstration project to use thin-film cells made at Chronar's Port Jervis, New Jersey, plant.

The Austin, Texas, municipal electric system is planning a $2.8 million test program with a 300-kW array. The city has called for supplier bids on a single-axis tracking flat-plate system it hopes to have installed by late 1986 for at least one year of testing. Elsewhere in the Lone Star state, an 18-kW flat-plate array feeds a battery bank for the uninterruptible power supply of El Paso Electric Co.'s Newman combined-cycle station.

New Mexico's rugged and remote terrain makes photovoltaics the power supply of choice for certain applications. Some 18 dozen 800-W modules power water pumps throughout the state, thanks mainly to generous tax credits. A 100-kW system is operating at Lovington on the grid of the Lea County Electric Cooperative, Inc., as part of the DOE–EPRI test program. The Southwest Region Solar Experiment Station is testing a 40-kW unit at New Mexico State University that is connected to the El Paso Electric grid. The solar experiment station is also testing 120-W and 1.2-kW modules. In Santa Fe, a 2.8-kW residential array is tied to the Public Service Co. of New Mexico distribution system.

Farther west, Arizona Public Service Co. has monitored a 225-kW tracking, concentrating PV array at Phoenix's Sky Harbor Airport since 1982. Although system performance was limited by problems with its inverter, it has achieved an average availability of 85% since a new inverter was installed over a year ago, according to Joseph McGuirk, manager of research programs. The utility also monitors the performance of a 4.4-kW residential system that has operated virtually trouble-free on a Yuma home since late 1982.

McGuirk says Arizona Public Service is planning a five-acre test center at its oil and gas-fired Ocotillo plant near Tempe. The project calls for long-term evaluation of up to 100 kW of PV modules from five or six different manufacturers beginning next year. "We are looking for cost-effective ways to supplement our current generating technologies. We know there will continue to be cost improvements in PV technology, and we want to be prepared to take advantage of these improvements," he adds.

In equally sunny southern California, San Diego Gas & Electric Co. is undertaking a technical and market study of a planned 37-townhouse demonstration of rooftop solar modules near Carlsbad. The project is a joint venture of home developers and a PV distributor. According to Don Fralick, an SDG&E engineer, six of the townhouses will be equipped with performance data recorders supplied by Sandia, which will also provide a weather monitoring station. The utility's role will involve monitoring demand, PV performance, power quality, and safety. Says Fralick, "We saw this project as an opportunity to study these issues before major penetrations of PV systems start occurring." Eventually, Fralick adds, up to 112 PV systems could be installed.

Elsewhere, SDG&E installed a 2-kW rooftop unit on company-owned residential property adjacent to its Del Mar substation and, in addition to that unit, monitors the performance of a 16-kW array mounted atop a local convenience market.

Perhaps the most extensive PV R&D effort by any utility is that of PG&E, which has both independently and in cooperation with EPRI operated and monitored numerous systems at its San Ramon engineering research laboratory for several years. Stephen Hester, a staff engineer who manages the testing, says about 40 modules are operating, including some 30 flat-plate systems.

In addition, a Varian Corp. 175-W concentrating (1000 ×) module, using gallium-arsenide cells, has recorded efficiencies as high as 16.9% at San Ramon, while a 2.6-kW single-crystal silicon concentrator (33 ×) module mounted on a Martin Marietta Corp. two-axis tracker has generated 13.75 MWh in three years of operation. PG&E is also testing thin-film solar cells from several manufacturers, reporting some performance degradation in these first-generation thin-film devices after as little as two months of testing.

Elsewhere, the northern California utility plans to monitor at least three customer-owned PV arrays beginning late this year; power ratings on these systems range from 2 to 20 kW. The 6-MW Arco Solar central station demonstration on the Carrisa Plains is already providing important data for the PG&E analysts. PG&E recently began its own conceptual design for a megawatt-scale central station facility, which it may someday decide to build.

PG&E also cosponsors, along with SCE, EPRI, and DOE, continuing R&D by Westinghouse on the dendritic web method of producing high-quality silicon sheet for lower-cost solar cells. PG&E, which has supported the dendritic web program since 1980, has taken delivery of about 80 modules made from sheet silicon, installing 2 kW atop the Veterans Memorial Building in Davis, with the rest going on test stands at San Ramon. □

duction is not much of a problem," says Taylor. "With the production technology defined and in place, you can make as many megawatts worth of cells as you want.

"Some of the key questions now relate to the hardware you have to wrap around the cell—the lens and housing. How fast and how cheaply can those be made and what are the capital requirements to do that? Can you integrate those steps into a module production line? Can industrial robotics and automation help make it happen? We expect to be working heavily on those problems over the next year," explains Taylor.

If the development program with Acrian is successful, EPRI research managers envision commercialization of the concentrator cell within four or five years. Within three or four years, the plan is to produce sufficient hardware for a megawatt-scale demonstration. The overall effort could represent a research investment of $30 million by EPRI and the utility industry.

To Cummings, an important part of the story of the concentrator cell was the R&D approach that brought 25% efficiency to reality. "We have always maintained that to make PV technology economic for utilities, the focus had to be on increasing cell efficiency. Sure, a lot of companies are in the business making lots of product, but to get utility-scale economics, high-volume production alone is not going to make it. With the concentrator cell, we felt there was no point trying to manufacture something until we had a cell with the efficiency we know is needed.

"Now, you don't get high-efficiency cells by just being lucky. You have to focus on fundamental device physics and understand as much as possible about what is going on in the cell. Plus, there has to be continuity in the research and in the program management. Utilities have recognized this issue, and they have supported us in this effort," continues Cummings.

Progress with cells made from semiconductor materials other than silicon also bodes well for success with concentrating PV systems. Researchers at Varian Corp. and Sandia National Laboratories recently reported 26% efficiency with experimental vapor-deposited aluminum gallium arsenide cells at 753 × concentration. They also report maintaining efficiencies exceeding 25% at 1026 ×. Such performance levels are believed to be the highest reported to date for any PV device.

### Silicon sheets

Crystalline silicon cells still hold promise for meeting utility efficiency and reliability targets, although the outlook for cost reductions remains uncertain. The research challenge is to grow high-quality single crystals as continuous thin (150-$\mu$m) sheets or ribbons at high rates (greater than 15 $cm^2$/min). Several technologies for making monocrystalline silicon sheet have been developed, but none has approached this growth rate on a continuous basis while maintaining high cell efficiency.

Most commercial cells today are made from crystals grown by the Czochralski method, in which an ingot of crystal is slowly rotated and withdrawn from a vat of molten silicon, then sawed into thin (250-$\mu$m) wafers for manufacture into solar cells. But in this process, as much as half of the feedstock silicon ends up as contaminated slurry. Sheet silicon could eliminate the wastage and thus lower the materials and manufacturing cost.

The dendritic web method of producing sheet silicon has fared well over the years in competition with other approaches and has benefited from continuing support under the federal PV research program managed by DOE. Developed by Westinghouse Electric Corp., in recent years the web technology program evolved into a cooperative research effort with additional funding from Pacific Gas and Electric Co. (PG&E), Southern California Edison Co. (SCE), EPRI, and DOE. But although progress is being made, EPRI researchers believe a sustained long-term commitment will be required if silicon web technology is to meet utility production and cost requirements.

Based at Westinghouse's Large, Pennsylvania, laboratories outside Pittsburgh, the dendritic web program has made significant strides. Cell efficiencies of 13.5% and growth rates of over 35,000 $cm^2$ per furnace per week have been achieved, but a fivefold improvement is still needed to reach production levels that could serve the utility bulk power market. That goal translates to producing an 8-cm-wide ribbon at 2 cm/min 95% of the time.

EPRI's perspective on the dendritic web is that 18% efficient cells can probably be achieved in the near future, but reaching the growth rates needed for both low manufacturing cost and reasonable return on investment for the processing equipment will probably require another five years of R&D.

Meantime, however, researchers agree it is important to begin manufacturing development. To that end, Westinghouse has announced a commercialization plan for its dendritic web technology that is aimed at putting into operation by 1990 an automated production facility capable of manufacturing modules that are 15% efficient with a 20-year design life at a cost of $1/Wp (in 1985 dollars).

C. M. Rose, manager of PV programs at Westinghouse, says the commercialization plan involves establishment of a joint venture with a foreign government. "Negotiations are nearing completion for the design, assembly, and operation of a semiautomated dendritic web module pilot production line at the current Pennsylvania facility," says Rose. After that, the plan calls for a semiautomated offshore plant to supply commercial product for near-term, high-value applications.

The final phase of the plan calls for design and installation of a fully auto-

## PV HISTORY: NOT JUST A CURRENT AFFAIR

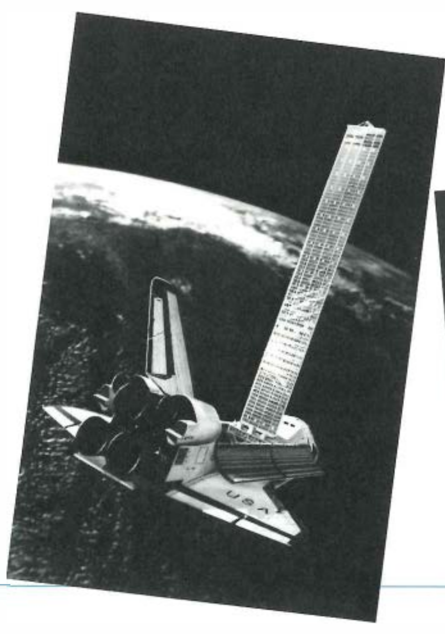
Although widely regarded as a high-technology creation of the space age, PV cells in fact have a much longer history; knowledge of the fundamental principle of their operation even predates Edison's incandescent lamp by 40 years. At the age of 19, the French physicist Edmund Becquerel observed in 1839 that a small voltage was created when one of two metal electrodes was placed in a weak conducting solution and the apparatus was exposed to light. Thus noted, little became of the photovoltaic effect until the 1870s when it began to be studied in solids, particularly selenium. (The name Becquerel would later be forever etched in history by Edmund's son, Henri, who shared the discovery of radioactivity with Pierre and Marie Curie.)

By the 1880s the first selenium solar cells were exhibiting efficiencies of 1–2%. Selenium's sensitivity to the visible light spectrum led to its use in photometric devices, and it is still found in today's light meters. But despite visions by early inventors that selenium cells would someday compete with the electric dynamo as a means of generating large amounts of power, selenium's low theoretical limit of efficiency made the development of practical PV cells await the arrival of quantum mechanics in the 1930s and, later, the field of solid-state physics to explain how the cells converted sunlight directly into electricity.

Researchers at Bell Telephone Laboratories stumbled onto the silicon solar cell almost by accident in the 1950s. One group was struggling to boost the efficiency of selenium cells in an effort to develop a remote power source for communications equipment. Other researchers, in quest of a better rectifier, found that adding impurities to silicon improved its electrical efficiency. When the silicon rectifier was exposed to light, a surprisingly strong current was generated. As a result, Bell scientists were soon demonstrating 4% PV efficiency.

Pursuit of the silicon solar cell began in earnest and the efficiency of experimental cells reached 6% by 1954. The world marveled at the news, with Bell Telephone System advertisments of its solar battery noting the "great possibilities for telephone service and for all mankind." But despite the achievement of efficiencies as high as 15% in experimental apparatus, the solar cell seemed doomed to become nothing more than a scientific curiosity. It was exceedingly expensive and had to be handmade from very pure silicon, which—although the most abundant element in the earth's crust—then cost $80 per pound.

But the silicon cell was saved from the museum shelf by Sputnik, the orbiting Soviet satellite launched in October 1957 that sent the United States into a headlong space race. Almost immediately, the silicon cell was recognized as the best hope for providing a few watts of onboard power for satellites without excessive weight; cost was of little concern. When the American Vanguard satellite went into orbit in 1958, it carried PV cells. The space age and the silicon era had begun in tandem. □




Collapsible 105-ft solar cell wing-tested by space shuttle Discovery

Vanguard satellite that carried first space-power photovoltaic cells

mated, 25-MW/yr commercial PV plant to produce 14.5% efficient, \$1/Wp flat-plate modules for utility use. "Economic analyses indicate that 15% module efficiencies and 180,000-$cm^2$/week web growth rates are required to achieve production cost goals of \$1/Wp demanded for large-scale utility application," explains Rose. "Demonstration of these efficiencies and production levels is the ultimate objective of the jointly sponsored development program, and we hope they can be met in 1987," he adds.

### Thin films

A very different kind of PV cell than that made from single-crystal semiconductors has rapidly garnered much of the world's hope and R&D attention as the leading PV technology that promises to make solar cells widely applicable and affordable. These cells are thin films of amorphous silicon or silicon germanium (a-Si or a-SiGe) or polycrystalline materials, such as copper indium diselenide or cadmium telluride. Each is sensitive to a specific part of the light spectrum; used in combination they can, in principle, convert more of the light to electricity than can conventional silicon crystals. Moreover, the materials can be vapor-deposited on foreign substrates (glass, for example) in layers 0.5 $\mu m$ thick to yield complete modules in fewer steps than are required for conventional cells.

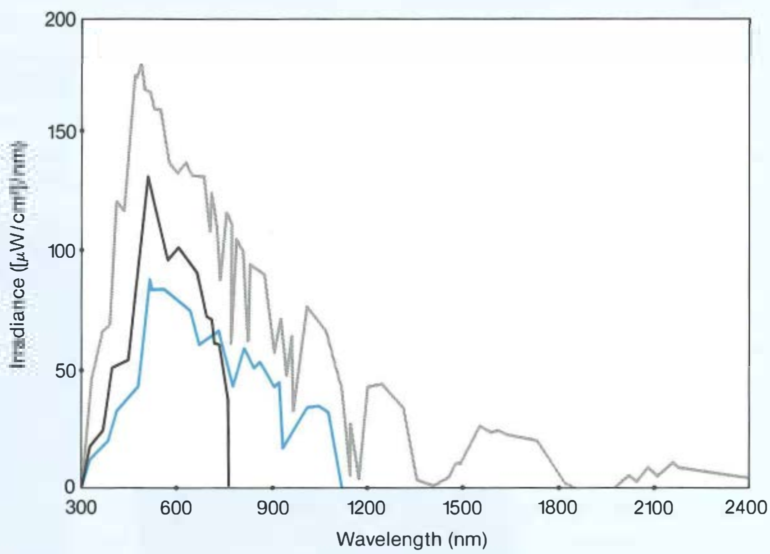
The excitement about thin films stems from the potential to deposit multiple layers of semiconductor materials or alloys at high rates of production. Each layer in a multijunction cell absorbs only part of the light, letting other parts of the spectrum pass through to be absorbed by the layers underneath. Because they absorb more light, including the diffuse fraction that concentrator cells cannot capture, tandem thin-film solar cells have the potential to be economic in regions not known for their sunny climes (i.e., beyond the Southwest). But, as with other PV cells, efficiencies, cost, and the volume and rates of production of current thin-film technology leave much room for improvement.

John Crowley, who manages EPRI's thin-film research activities in the fast-moving amorphous materials field, says the technology is much less advanced than conventional or concentrating cells. "The integrated-circuit processing techniques that EPRI hopes to apply to making high-concentration cells are not that far removed from the state of the art of very large scale integration (VLSI) technology that puts thousands of circuits on chips that go into supercomputers and the like. The analogy with amorphous silicon is that we're just now learning how to make transistors, and the first integrated circuit had only about eight transistors on it.

"For amorphous thin films to really make it as PV technology, we have to go from simple transistors to VLSI technology," says Crowley, continuing the analogy. "Although there are commer-

**Multijunction Cells: Optimizing PV Efficiency**

Multijunction solar cells made from thin films of amorphous photovoltaic materials can convert more light to electricity than can conventional cells. Layers of different materials—each treated to respond to a specific portion of the light spectrum—are deposited on a single glass substrate in a multijunction cell. The top graph shows total insolation as distributed across the light spectrum; the graphs underneath correspond to the portions of this light converted by two layers of a multijunction cell. Thin-film PV cells can be made opaque or translucent and can be made in many shapes and sizes.



cial amorphous silicon cells now on the market with efficiencies from 4 to 6%, my feeling is it will take at least 10 years of R&D to get cell efficiencies up to 18%, which is the level that will be needed for 15% efficient modules of about 2 $m^2$ to produce economic bulk power."

As Crowley points out, at least three American PV cell makers are now commercially offering amorphous silicon cells. Solarex Corp. is producing telemetric devices for the original equipment manufacturing sector. Arco Solar Inc.'s square-foot thin-film module is being marketed as a battery charger and remote low-power source. Chronar Corp. is making cells for various applications and has announced plans for three new production facilities, plus a 100-kW thin-film power plant demonstration with Alabama Power. Energy Conversion Devices, Inc., has indicated it, too, will make amorphous silicon cells for the consumer electronics market under joint ventures with Sharp Electronics Corp. of Japan and Standard Oil of Ohio, Inc., in the United States.

"Experimental thin-film multijunction cells of about 1 $cm^2$ have reached 12% efficiency in the laboratory," reports Crowley, "and the prospects for getting to 18% at that size are very good. But the real challenges in this field—large-area deposition of thin films and high production rates—bring us right back to the fundamental physics because we just don't understand well enough what happens in those micrometer-thick layers to be even close to knowing how to turn out 18% efficient cells at 500,000 to 1,000,000 $m^2$ annually from one machine and produce at a level of 25–50 MW/yr."

Robert Annan, director of DOE's PV division, agrees that the challenge in thin films includes gaining a better understanding of the physics of the technology. "Most of the emphasis for the future in DOE's PV program is in multijunction thin-film cells," comments Annan. "We're trying to manage the incrementalism of the technology—to understand where it's going, what its limits are, and what funding levels are needed to reach the limits."

The Japanese are widely regarded as having the technologic edge in several areas of amorphous materials development, having seized it several years ago for broad applications in consumer electronic and semiconductor products. Worldwide, research investment for non-PV applications greatly exceeds that for amorphous solar cells. Some photocopiers already use amor-phous materials as an electrographic element. But over a dozen Japanese organizations are intensively pursuing amorphous PV technology under a coordinated government, industry, and university research program.

Many American firms outside the PV industry are active in the field as well, including Xerox Corp., RCA Corp., Exxon Corp., Eastman Kodak Co., and Polaroid Corp. Other potential uses for amorphous semiconductors include rerecordable video disks, thin-film transistors for high-resolution liquid crystal displays in flat-panel television and computer screens, electronic signal processing devices, and photoreceptors for laser diodes in fiber optic communications equipment.

EPRI's program in amorphous materials for PV application, begun in 1983, emphasizes basic research into high-quality, low-band-gap (the most light-sensitive) alloy materials, the kinetics of thin-film deposition, device physics, and long-term cell stability. Fundamental challenges include maintaining very high alloy purity in production and either preventing or limiting the seemingly inevitable performance degradation that occurs over time when the materials are exposed to light—an important concern. Participating in the work are Princeton University, Poly Solar, Inc., the University of Illinois, Pennsylvania State University, and the University of Delaware.

According to John Cummings, "It's essential to see if a multijunction thin-film device is in the cards that could make photovoltaics more widely applicable and economic in a geographic sense. That's why we're working on the alloys, the deposition processes, and modeling the physics—really focusing on the fundamentals. The work we've sponsored with Stanford on the concentrator cell shows us the approach we must take. Besides giving us a path to a near-term PV option for utilities, the concentrator cell work also has given us an approach to the R&D that may eventually yield an option in thin-film technology."

Part of the objective of EPRI's effort in thin films is aimed at promoting cooperation and a cross-fertilization of insight among researchers in the amorphous materials field, especially between industry and the academic community. The Institute's program is conducted in close coordination with an advisory committee consisting of representatives from leading industrial firms in amorphous silicon R&D.

EPRI is also attempting to encourage international interaction, especially with the Japanese. Last July EPRI and Japan's Ministry of International Trade and Industry and the New Energy Development Organization sponsored a three-day workshop in California that brought together nine leading research scientists from Japan and eleven from this country, representing industrial, government, and academic centers for amorphous materials research.

"The point of the workshop was to try to get the most informed technical consensus on the key issues that require resolution for successful development of materials for use in tandem amorphous silicon cells," explains EPRI's DeMeo. "Discussions at the workshop clearly indicated that the research and physical understanding are at a very early stage. By seeking consensus from the participants, we were able to broadly define research needs to address the technical issues over the next 5 to 10 years."

Commercial development of thin-film photovoltaics continues apace, meantime. James Caldwell, president of Arco Solar, says that the company "is on the verge of moving totally and directly from crystalline silicon to thin films—not just amorphous silicon but also copper indium diselenide. For us, the transition will occur within three to five years. We have committed $10 million to build a full-scale manufacturing facility and to design a major grassroots factory for thin films to come on-line in late 1987. I believe we'll see warranted thin-film product efficiencies above 10% in three years."

In addition, Chronar and Southern Electric Investment Corp. (a unit of The Southern Company) have announced a joint venture to build a 1-MW/yr amorphous silicon single-junction thin-film cell manufacturing plant near Birmingham, Alabama, expected to be operating by late 1986. The planned $7.2 million facility is intended to produce 4–6% efficient cells, some for use by Southern's Alabama Power for demonstration and testing. "We feel that as long as we're on the outside, we'll never know exactly what the prospects really are for these cells," says Herbert Boyd, Alabama Power's manager of forecasting and strategic planning. "Our goal is to get involved and learn for ourselves the ins and outs of the technology." Boyd says Alabama Power is very interested in the prospects for thin-film photovoltaics to provide a peak generating option beginning in the mid 1990s.

An important issue for Arco Solar, as well as for other cell makers, is whether today's markets for remote power sources and consumer products can provide the necessary revenue to help bring costs down sufficiently to open up the utility central station market. "My belief is the market is relatively inelastic," affirms Caldwell. "We won't reach another market plateau until prices are approximately half what they are today. We believe first-generation thin films are capable of making that transition."

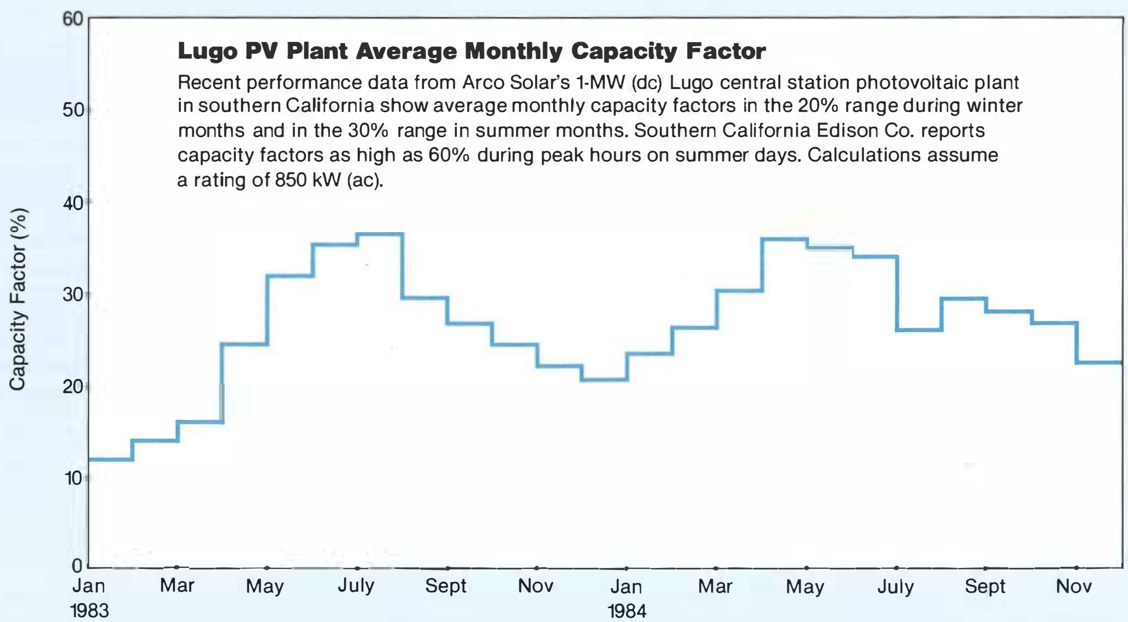
### Central station PV power plants

In addition to betting on thin films as the technologic bridge to wide-scale utility use of photovoltaics, Arco Solar has taken bold steps to demonstrate the central station PV power plant in advance of the time it is truly competitive with conventional generation.

Within eight months in 1982, the company built a 1-MWp flat-plate power plant on 20 acres of SCE land adjacent to SCE's Lugo substation near Hesperia in the San Bernardino mountains east of Los Angeles. The single-crystal silicon cells are contained in some 27,000 modules mounted on 108 dual-axis computer-controlled pedestals that track the sun's course across the horizon. Power is converted to alternating current through three high-capacity inverters and increased in

**Lugo PV Plant Average Monthly Capacity Factor**

Recent performance data from Arco Solar's 1-MW (dc) Lugo central station photovoltaic plant in southern California show average monthly capacity factors in the 20% range during winter months and in the 30% range in summer months. Southern California Edison Co. reports capacity factors as high as 60% during peak hours on summer days. Calculations assume a rating of 850 kW (ac).



voltage for delivery to the SCE grid.

According to Joseph Reeves, SCE's manager of renewable energy systems, "Arco Solar's demonstration plant has shown that photovoltaics is well-suited to the Edison grid as a peaking resource. Since coming on-line the plant's capacity factor during our peak hours of the day in the summer months has generally been above 60%. Combine this with unattended operation, low maintenance expense, no water requirements, and no air emissions, and the potential for photovoltaics becomes clearly evident."

Not content with 1 MW, in late 1983 Arco Solar began construction of a 6.5-MW plant and substation on 160 acres of PG&E land on the Carrisa Plains east of San Luis Obispo. The first phase of installation consisted of 756 two-axis pole-mounted trackers, each containing about 5 kWp of crystalline silicon cells with laminated glass reflectors to boost power output. The modules feature an improved square cell design to increase packing density and boost module efficiency from about 9% to 11%. A novel field installation technique permitted construction of a plant four times that of the Lugo site in approximately the same amount of time. Arco Solar later added 43 trackers supporting larger module panels without glass reflectors to bring the system capacity to 6.5 MW.

In July 1984 a 1-MW field of Arco Solar modules mounted on low-profile horizontal-axis trackers was installed adjacent to the Sacramento Municipal Utility District's Rancho Seco nuclear plant under a program funded by SMUD, DOE, and the California Energy Commission. Another 1-MW increment began construction this year and is nearing completion.

Not even Arco Solar argues that any of the central station projects are economically competitive with conventional generation, and the company will not say just how much it invested in the Lugo or Carrisa Plains plants. But many observers agree that a powerful statement and a vision of the future are embodied in these quiet-running, unattended solar generating stations. Both SCE and PG&E report good power quality and a generation pattern that matches well with the utilities' peak demand profiles.

"These were very important statements for us to make," notes Arco Solar's Caldwell. "The solar energy tax credits allowed us to make the statement, but now we have actual operating central station PV power plants in the field and we're generating invaluable experience and confidence regarding such features as modular deployment speed, power quality, and reliability. These plants also have essentially zero operating and maintenance costs. Now it's up to us to prove we can bring costs in line. These are exciting times in the photovoltaics business because the promise has become a reality."

Says EPRI's DeMeo, "We're also enthusiastic about these central station plants because they have verified—at least over the near term—some of the key expected advantages of photovoltaic power. Modularity in design and construction has been shown conclusively. The ability to operate these plants largely unattended so far bodes very well for low operating and maintenance costs. In addition, these plants are generating significant amounts of net electric energy essentially in agreement with predictions, and no major surprises have arisen. Arco Solar deserves considerable credit for demonstrating these crucially important features for the benefit of the photovoltaic community."

The prospects for photovoltaics to someday assume an important role in the generation mix for many utilities seem bright indeed. Notes Carl Weinberg, chief of PG&E's Engineering Research Department, "We certainly feel the technology has the potential to make a significant impact should it continue to come down the cost curve. The technology's cost and performance have really improved in the last 10 years, and if those strides continue, the potential for cost-effective utility photovoltaic power is clear."

Continuing good prospects for technical progress and for sustained business development point to a bright future for photovoltaics as a source of bulk electric power. The challenge for the next decade, researchers say, is to push the technology to its physical limits while simultaneously expanding markets and building user confidence. ■

**Further reading**


*Photovoltaic Manufacturing Cost Estimation: Preliminary Assessment*, Vol. 1, *Technical Report*. Final report for RP1975-1, prepared by Research Triangle Institute, Inc., forthcoming. EPRI AP-4369.

Solar Energy Research Institute. *Photovoltaics Technical Information Guide*. February 1985. SERI/SP-271-2452.

*Integrated Photovoltaic Central Station Conceptual Designs*. Final report for RP2197-1, prepared by Black & Veatch Engineers-Architects, June 1984. EPRI AP-3264.

*Proceedings of the 17th IEEE Photovoltaic Specialists Conference—1984*. Kissimmee, Florida, May 1984. 84CH2019-8.

E. A. DeMeo and R. W. Taylor. "Solar Photovoltaic Power Systems: An Electric Utility R&D Perspective," *Science*, Vol. 224, No. 4646 (April 20, 1984), pp. 245–251.

*Photovoltaic Power Systems Research Evaluation—A Report of the EPRI Ad Hoc Photovoltaic Advisory Committee*. Final report for RP1348-15, prepared by Strategies Unlimited, December 1983. EPRI AP-3351.

Ralph Whitaker. "New Promise for Photovoltaics," *EPRI Journal*, Vol. 8, No. 6 (July/August 1983), pp. 6–15.



This article was written by Taylor Moore. Technical background information was provided by John Crowley, John Cummings, Edgar DeMeo, and Roger Taylor, Advanced Power Systems Division.

Direct technical assistance to member utilities is being used to speed the latest R&D results into practice. Recent experience of EPRI's Coal Combustion Systems Division illustrates the advantages of direct personal contact.

# Technology Transfer One-to-One

Site-specific technology transfer is the electric utility community's newest way of getting definable, measurable value out of its R&D investment in EPRI. Utility and Institute staff members are telephoning each other and knocking on each other's door ever more frequently these days, cooperatively tailoring EPRI research results to the equipment and operation of both old and new utility plants and systems.

Begun in 1972, the Institute's R&D now represents a cumulative investment of about $4.0 billion, including the value of funds, facilities, and services contributed by utilities, manufacturers, government agencies, and others. Membership dues constitute $2.5 billion of this figure, and the pace of such revenue today is about $330 million annually.

But dollar investments do not unfailingly measure the output in practical terms. Nor do technical reports—the traditional symbol of research progress and completion—and EPRI is now turning out reports at a clip of nearly 700 titles a year. In fact, as such numbers grow and the library becomes larger, retrieval of the most specific, directly applicable results becomes more difficult. This works against the urgency (which is also growing) that research results come into commercial practice and that they be on the shelf at a supplier or on-line at a utility so as to yield a calculable return on the dollars invested.

Direct technical assistance to member utilities is therefore becoming a more frequent EPRI practice. Examples from recent experience of the Coal Combustion Systems (CCS) Division afford a timely look-in on the phenomenon. There is a new atmosphere among CCS research managers and their utility counterparts today—an enthusiasm that comes when initiatives are welcomed, expectations are positive, and worthwhile results are being achieved, often in only months.

#### Organizing to aid utilities

Kurt Yeager, CCS division director and an EPRI vice president, observes that one-to-one technology transfer is not a totally untried Institute practice. "The Nuclear Power Division was at it earlier than we were," says Yeager. "Nuclear power was a fairly new technology, the industry realized there was a lot it didn't know, and members were glad to call on EPRI, in fact, to demand support.

"But in the fossil fuel business," he goes on, "utilities have been operating plants for over 80 years. Coal-fired systems were seen to be mature technology. Their owners understandably were not so quick to see R&D as a tool for getting at near-term problems or to call on a relatively new organization for answers."

One-to-one interchange with EPRI members has therefore come about more slowly for the CCS division. But generic investigations in such areas as component reliability, scrubber chemistry, particulate control, coal preparation, combustion control, water conservation, and waste handling have produced useful results, especially a number of guideline documents—manuals for equipment and process design, selection, and operation. The word is getting around, questions and answers are being exchanged, and CCS direct technical aid in the past two years has come to be managed and accounted for among planned division activities.

The CCS division has categorized several approaches to utility assistance, according to Rolf Manfred, senior technical manager. Manfred has divisionwide responsibility for effectively combining new technologies—new R&D products—in their application by individual utilities. "One utility transaction has involved review of the system design specifications for a planned generating unit," he says, "and chances are that this kind of interaction will increase."

In other cases, where R&D results may improve existing utility equipment operations, CCS staff members have used field visits as the basis for tailoring applications. In still other instances, EPRI research projects use utilities and their equipment as test beds; utility applications of the findings for their individual installations are by-products of that research.

"There's also a kind of transaction that can be called an application project," explains Manfred. "It's initiated to commercialize a single R&D product that's ready for utility use." The product may be a new material, a valve, a chemical, a computer code, a component selection guideline, or an operating procedure that needs only a few instances of authentic utility application to get it off the ground. Because many of the candidates involve particulate and $NO_x$ control, flue gas desulfurization, and water- and waste-handling technologies, Walter Piulle of the Environmental Control Systems Department also is involved with CCS field representatives and utilities in arranging the necessary special-purpose projects.

### Design review for Salt River Project

Coronado Unit 3, planned by the Salt River Project (SRP), is perhaps the most comprehensive example of CCS technical aid, and one that had an ideal administrative origin. A. J. Pfister, the utility's general manager (and EPRI's Board chairman at the time) decided early in 1984 to make all possible use of EPRI technology in the design of the new 350-MW coal-fired unit.

Pfister broached the matter to Yeager in May, and the two men called on their respective staff members to set in motion a methodical review of all the major system design specifications. Moreover, in what was also a novel step, SRP's consultant, Black & Veatch Engineers-Architects (B&V), became an integral part of the process.

By the time groups from SRP, B&V, and EPRI all came together in August 1984, the CCS division had generated a list of 111 R&D products that might be relevant—guidelines, processes, computer codes, items of hardware, and technical evaluations. Recognizing the time span over which the Coronado unit would be designed and built, SRP also had called for potential products, that is, R&D findings expected as far as three or four years in the future.

As matters turned out, the checklist was not so much an agenda for the August meeting as it was a means of becoming aware of the very latest R&D findings. A. W. Staley, SRP's project engineer for the Coronado unit, points out that B&V was well schooled in EPRI's published research. "This fact surfaced immediately in the meeting. They routinely assimilate EPRI findings for use in the course of their standard design work."

But preparing research results for publication takes time, far more than how long it takes to print the report, and SRP wanted to learn what was coming along next. Essential conclusions are often known to EPRI project managers well before the contractor's report is even drafted. "This is the insight we wanted," Staley goes on, "plus whatever information EPRI could comfortably share from new investigations that might be leading in new directions."

During the next nine months, a series of seven specification documents came to EPRI's Manfred, to be reviewed by individuals and teams from five of the seven research programs in the CCS division. Pfister had avoided setting restrictions on his original request, so the EPRI research managers were free to suggest even such major changes as higher steam temperatures and pressures and additional reheat.

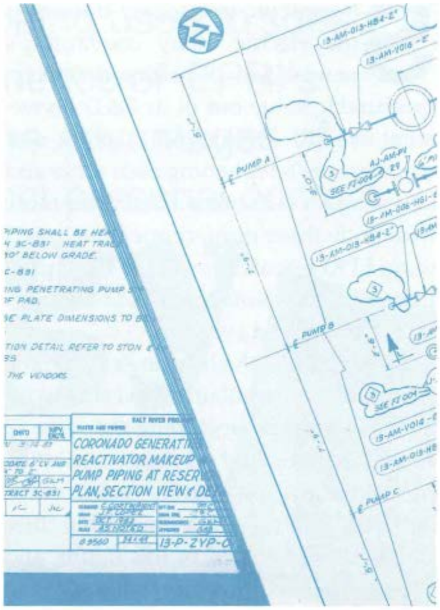
This latitude was welcome, but CCS reviews mostly took the practical form of careful reading followed by qualitative questions and suggestions. These were in specific contexts of parameter ranges and limits, materials, instrumentation, controlling specification documents, additional or different options for various equipment and process items and configurations. Again, Staley explains. "We wanted to avoid ambiguity, and we wanted expertise to detect outdated requirements. I think, for instance, of measures that would give longer life or more reliability than before, especially for the boiler; that's the system with the highest outage rate."

**Boiler and scrubber specifications**

Analysis of the root causes of failures in fossil fuel boilers goes back almost to EPRI's beginning; it has led to a growing list of reports on individual components. As the work continues, it is leading also to guidelines for equipment design, selection, and operation. Barry Dooley of the Availability and Life Extension Program was one of those who reviewed SRP's boiler specification for Coronado Unit 3. He counts the resulting markup a valuable contribution because of the opportunities to suggest new practices aimed specifically at avoiding availability loss.

Knowing what EPRI has cataloged as the major availability loss items in boilers, Dooley focused on those most likely for a southwestern U.S. plant, influenced by such factors as coal type, dispatch pattern, and O&M practices. One example is overheating and long-term creep in superheater and reheater headers and tubing; another is fire-side erosion in the economizer section. "The boiler manufacturer's specs usually include data on materials temperature limits," explains Dooley. "What we suggested was that the Salt River staff require thermocouples to be built in. That way they could monitor actual temperatures during early operation and take steps to avoid failures later on. They'd also find out what effect that had on other operating parameters."

Flue gas cleanup provisions for the Coronado unit also came under scrutiny. Stuart Dalton, manager of the Desulfurization Program, remembers the orderly sequence in which the scrubber design was reviewed. "There was even a prespec meeting—B&V hadn't yet drafted the document—when we simply talked through various issues and suggested some reports and papers for them to review, recommending contacts for them



Joint review of system design specifications linked Salt River Project engineers, Black & Veatch designers, and EPRI research managers in a cooperative search for opportunities to apply late R&D results to the design of a new generating unit.

to make with some of our contractors.

"For instance, we were sponsoring some work in scrubber materials, and we already knew that borosilicate glass looked promising for places like the outlet duct of a scrubber. That's one of the worst places for corrosion—very low pH. Most alloys and linings turn out to be inadequate there."

It was January of this year when the draft specification was complete, and early February when Dalton prepared a three-page memo of questions and commentary for discussion with SRP and B&V engineers in an all-day session at Phoenix. Dalton recalls three points of design that especially benefited from the exchange. "One was materials. Another was some suggestions we had for the configuration of the mist eliminator.

"It's basically an inertial separator," he explains, "where moisture in the scrubbed exhaust gas stream impinges on the zigzag blade surfaces and is drained away. But you can design the scrubber with space for the largest droplets to fall before they get into the separator. That eases a frequent problem of scaling in the passages. On the basis of testing elsewhere, we had some ideas on wash nozzle design and washing frequency for the mist eliminator, too," Dalton adds.

The other major contribution was in damper design. Historically, the dampers used to adjust exhaust flow or isolate scrubber modules are a focus of corrosion; and for this and other reasons it often becomes difficult to close them tightly. Research sponsored by Dalton's program, but not yet published at the time of the SRP design review, yielded a draft damper specification incorporating some new ideas on materials, seals, and mechanical design.

Dalton is confident of what R&D products like these are worth in terms of savings to users. Aware of the CCS division's rough estimate of a $2 million value for the scrubber design suggestions, Dalton remarks, "That could be saved if you avoid, say, one outage a year for plugged mist eliminators and one need in five years for scrubber relining."

#### Particulate controls

Robert Carr, director of EPRI's Environmental Control Systems Department, studied the particulate control specification. "It was especially interesting," he recalls, "that the Salt River staff had decided on fabric filters—the first time for them. I think they were encouraged that a number of baghouses elsewhere in the West have done very well.

"We identified about a dozen points for discussion with Salt River and Black & Veatch," Carr continues. "Several of these dealt with details, but the major one was a summary review of two fabric filter cleaning technologies, reverse-gas and shake-deflate."

Reverse-gas technology is used in about 90% of current baghouses, according to Carr, and shake-deflate in the other 10%. Although its experience base is much smaller, shake-deflate seems to yield more-thorough bag cleaning and a smaller pressure drop during operation. Both factors permit a somewhat smaller baghouse (and therefore lower capital cost) for a given unit capacity rating. The smaller pressure drop also leads to improved heat rate and, consequently, lower operating cost.

A potentially adverse point, Carr observes, is that shaking fabric filters can be hard on them unless carefully done. Shake-deflate bags have lasted more than three years, but even so, the data base is much smaller than for reverse-gas cleaning. Further, there has been no experience with ash from the coal SRP plans to burn at Coronado Unit 3. What kind of fabric, how much to deflate a bag, how hard to shake it, how fast, and how often—all these were still unknowns.

All things considered, EPRI's air quality control research managers believed that shake-deflate technology made the best sense for Coronado Unit 3. SRP, having spent several months investigating both filtration options with suppliers and other utilities, as well as with EPRI, came to the same conclusion and decided to seek bids only on a shake-deflate design.

Carr concludes with a brief description of plans to develop comparative data on fabric types and operating routines for SRP's baghouse design. The effort will make use of EPRI's pilot-scale sidestream filter, a portable fabric screening system to be installed at one of the existing Coronado generating units.

#### Evaluating the review

Staley himself led the group meetings that followed EPRI's reviews of the boiler, the scrubber, and the baghouse. (Other components were the subject of fewer and more specific comments, transmitted in writing.) As many as 20 people from SRP, B&V, and EPRI sat in on these occasions, usually at the utility offices in Phoenix, with Staley calling on his experts in each technical area to introduce EPRI's comments for discussion, one by one.

The Coronado reviews were a special opportunity for resolving any sensitivities, especially architect-engineer perceptions of being caught in the middle and second-guessed. The possibility was largely eliminated in this instance by B&V's established practice of monitoring EPRI's research output. As for the utility engineers, SRP had long been an enthusiastic member and advisory participant in EPRI work. "Even so," Staley says, "we specifically reminded ourselves that we already own five coal-fired plants. We did the best we could with each of them, but they all have their nagging little problems anyway. We aren't perfect, and we wanted the best for Coronado Unit 3."

Staley is confident that SRP's and B&V's experts in each technology came away with better knowledge. "New light in gray areas" is how he puts it. "The scrubber coatings are an example. Because EPRI had tested some coatings, we were able to narrow down the options we would entertain."

There was no immediate SRP attempt to justify the Coronado design review by costing out various design refinements and their likely effects on capital and operating costs. However, as Staley reports, SRP formed a task force to quantify the utility's benefits from various applications of new EPRI technology, and both EPRI and B&V are represented in that group.

EPRI assessed the nearly year-long Coronado effort in two ways. Manfred compiled estimates and records of personnel time spent; the total came to nearly 550 manhours. The transaction was an unusual one, of course, a review of an entire unit design. It was also a special opportunity to evaluate the EPRI-utility interaction process itself, to learn how to package current R&D information, structure its smooth communication, and measure its effectiveness (especially in terms of return on the manpower invested).

Manfred elicited EPRI staff estimates of dollar economies attributable to specific choices made by SRP and B&V as a result of the reviews. These figures include some $7 million of capital cost in the baghouse and scrubber designs and about $360,000 of annual O&M cost in the boiler and baghouse, which together represent annual savings of perhaps $1.5 million.

Such an evaluation does not take into account the impressive amount of EPRI information, data, and R&D products already adopted by B&V in preparing the Coronado specifications. In Manfred's opinion (a tribute to the architect-engineer) the value of that earlier technology transfer probably exceeds the value of the entire consulting review.

In retrospect, the Coronado Unit 3 design review, although an instructive prototype, is not typical. There are relatively few instances of new generating capacity today. Utilities are more often looking to avoid new capacity, and their most likely interest is R&D that can improve the productivity or extend the life of existing plants.

## Unit availability at Pennsylvania Power

Pennsylvania Power & Light Co. approached EPRI with a different need for R&D assistance, although it will likely take advantage of some of the same CCS division expertise. This transaction began early in 1985 as the utility formulated plans for an engineered program to improve the availability of its existing generating units. James Geiling, PP&L's manager of power plant engineering, and Martin Cottrell, technical manager in that department, met with Manfred and John Parkes, manager of EPRI's Availability and Life Extension Program. Cottrell explains some of the background thinking.

"We realized that most work on availability focuses on the O&M aspects, usually with only minor equipment upgrades. Design limitations and the corresponding opportunities for design improvement haven't been systematically identified throughout a unit that's already in use. This is what we want to get at." PP&L's early actions, therefore, are to gather information from manufacturers, other utilities (including some abroad), EPRI, and others. The queries directed to EPRI alone are illustrative: (1) What design changes in the past 10 years (and separately for the 10 years before that) have pointedly addressed availability improvement; and (2) what current EPRI projects are relevant?

The early exchange with EPRI led to a two-day meeting where a dozen CCS and other research managers introduced and discussed with Geiling and Cottrell the availability implications of their work in some 18 technical areas. A few R&D applications with immediate potential surfaced right away, such as fabric filter cleaning techniques and instrumentation for boiler tube leak detection. Others have evolved in subsequent exchanges, as have potential opportunities for PP&L and EPRI to cosponsor research that would further the goals of both.

Late last summer, for example, PP&L was among the prospective bidders for a cooperative (10 utilities) demonstration of the techniques described in EPRI's newly published *Manual on Investigating and Correcting Boiler Tube Failures* (EPRI CS-3945). This two-year project is seen as a way to formulate effective management of boiler tube failures, including even a multiutility data base.

Texas Utilities Generating Co. is seeing better performance and cost savings at its Martin Lake plant, the results of cooperation in EPRI-sponsored research to formulate a trouble-shooting model for scrubber chemistry.

In another, different kind of initiative, PP&L asked EPRI to consider a thorough postmortem of an entire generating unit. Such research could be the means, among other things, of testing various NDE and diagnostic methods—"calibrating" them (as Cottrell says) with destructive tests and correlating the findings with the unit's operating history. The subject of such a postmortem should be a 30- or 40-year-old unit, preferably one that has been retired or placed in cold reserve, certainly one with extensive and accurate records. The outcome could be design and operating changes for newer units that would reduce long-term failure rates.

PP&L and EPRI are now discussing a limited project to pilot this concept. The work would build on PP&L's current root-cause analysis of drum cracking in one of two nominally identical 30-year-old boilers. The investigation would further the utility's program in availability improvement, and it would also provide EPRI and other utilities with some useful measures for extending the economic life of older generating units.

## Life extension at Boston Edison

Boston Edison Co. has as long an EPRI membership as any, but perhaps more important, it has long-standing advisory connections as well. Trying to pinpoint when and how the utility came to work closely with EPRI's CCS division is therefore difficult for Cameron Daley, Boston Edison's vice president for steam and electric operations.

It was in the mid 1970s, Daley recalls, when Boston Edison established what EPRI and its members now call technical information coordination—at minimum,

Overhauling a 24-year-old generating unit gave Boston Edison Co. the opportunity to develop guidelines for assessing usable machinery life and identifying cost-effective ways to extend it.

Photo courtesy of Paul Ferrino

**ENHANCING THE TRANSFER**

One-to-one technical interaction between research managers of the Coal Combustion Systems Division and engineers of EPRI member utilities reveals differences in substance, as well as in origins, organization, and conduct of the efforts. But there are at least five major common threads seen by Kurt Yeager, CCS division director, and other EPRI executives, for truly effective interchange. Most important is the attitude and often the personal initiative of utility officers and their senior managers. Commitment in what Boston Edison's Cameron Daley calls "the top of the house" works wonders.

Another thread is participation in EPRI's industry advisory committee structure. This is a way for utility people to gain confidence in EPRI's work and its people and also to help shape its programs. Although committee involvement is easier and more practical for a larger utility, a smaller organization finds participation really whets the appetite for other opportunities to draw value from Institute R&D.

An effective communication system within a utility and with EPRI—two-way communication in both cases—is a third common thread among utilities who make the most of R&D. The important thing is that EPRI's work be seen as a specific resource for timely problem solving. Smaller utility organizations may have an edge here, simply because there are fewer channels and organizational end points to be reckoned with.

The fourth commonality is closely related: problem solving by interaction between the directly concerned individuals at EPRI and the member utility. There must be opportunities for researchers and engineers to establish the personal rapport that encourages candor, confidence, and trust in their work together. Size of organization has nothing to do with achieving this happy state. But it begins at the top and diffuses downward by example.

A fifth practice that is obvious among the utilities most aggressively seeking out R&D applicability is some systematic attempt to audit and quantify the outcome—the value of the effort, the benefit or saving derived. Bottom-line figures tell the story for management executives, researchers, operating personnel, employees at large, shareholders, and members of regulatory agencies. □

the business of distributing EPRI reports and getting feedback on their applicability. Daley is specific. "It's absolutely key to get the publications to the right people. That way, when there's a specific question, first we search the data base. Then we call EPRI and talk with someone."

One recent Boston Edison problem dovetailed so perfectly with a planned EPRI research project that the utility became EPRI's prime contractor and one of its plants became the research laboratory. "About two years ago," Daley goes on, "our system planning people wanted us to look into longer operating lives for our generating units. We were just starting to work on it when EPRI solicited proposals for a member utility to develop guidelines on the subject. In this instance," Daley observes, "our calling EPRI was a matter of responding to an RFP."

Unit 6 at the company's Mystic plant was uniquely positioned, as Daley recalls. "It was just about to come down for a 22-week overhaul outage, including some major replacements, a perfect opportunity for metallurgical investigations, destructive testing, and so on. Boston Edison got the contract. And not only that, but our project manager really beat the bushes for subcontractors who would do more than just work on it, ones who would get into the spirit of the thing and share its cost."

John Scheibel, a project manager in the CCS Performance and Advanced Technology Program, confirms that about 70% of the project costs were paid or covered in kind by the utility team, which primarily included Sargent & Lundy, Combustion Engineering, Inc., and General Electric Co. "Mystic was down from October to March," Scheibel says, "and it really was a first-of-a-kind job in both approach and detail. The work involved more than 5000 tests of components."

Scheibel cites two examples of the research techniques used at Mystic. One was a test for creep damage in high-temperature areas, such as superheat and reheat outlet headers, main steam lines, and high-pressure turbine casings. Researchers used what they call plastic replication (making casts of small areas of critical surfaces). When the surface is properly prepared, such a replica mirrors the pattern of creep voids in the surface. A second replication, perhaps years later, will reveal any progressive change in the pattern, enabling a forecast of component lifetime and need for its replacement.

Data from components that have been overheating were another need, this one met by temperature probes to operate in conjunction with an EPRI-developed boiler stress and condition analyzer. By monitoring temperature excursions, a computer calculates the creep and thermal fatigue damage to be incurred in a given operating mode. The implications include forecasts of inspection intervals and changes in operation that would minimize progressive damage.

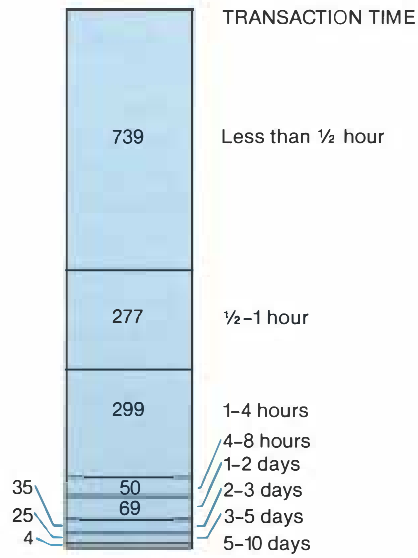
As expected in a major overhaul, the work at Mystic revealed needs for component repair or replacement. Also, according to Scheibel, "the project turned up things that will need attention soon—for example, a primary superheat outlet header that overheats and possibly will need to be replaced in the next five years or so."

But the main objective was to calibrate the 24-year-old oil-fired unit and develop a methodology for evaluating the rate and extent of changes (wear and tear) at some later date. This will enable Boston Edison to judge the wisdom and cost of actions required for Mystic-6 to operate economically beyond its originally planned lifetime. The methodology will become part of a generic guideline, joining the output of similar EPRI-sponsored research with other utilities involving other plant systems—coal-fired boilers, turbines, generators, and balance-of-plant components.

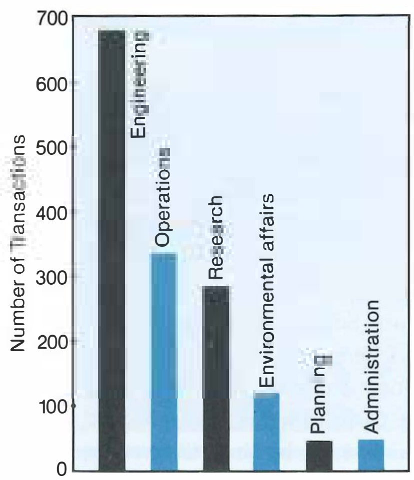
Plant life extension is not the only instance of Boston Edison's direct liaison with CCS division research managers and their projects. Others include dynamic modeling to improve heat rate and cut fuel costs, procedures for selecting feedwater heaters, measures for better reliability in coal pulverizers, specifications for flue gas scrubbers, and coal characterization. Five of these represent first applications of EPRI research results by a member utility, leading Daley to reemphasize that personal relationships

**Measuring Assistance to Utilities**

Staff members of EPRI's Coal Combustion Systems Division recorded 1498 individual telephone and personal contacts with utility personnel during just four months last summer. On the average, the 375 contacts of a single month put 325 individuals at 100 utilities in touch with 50 CCS men and women.




The 1498 contacts with utilities (not counting workshops and seminars) totaled about 400 man-days (of 8 hours each) for CCS staff members, about 7% of their time during the period. That total combines their telephone time and their advance estimates of the time required to follow through on the subjects discussed. The resulting median time per transaction was a little under 2 hours, even though nearly half were completed in ½ hour or less.




The four-month record of CCS-utility transactions involved 165 separate utilities and a range of subject matter. Predictably, engineering is the top area for R&D application.

are ultimately what move new technology into practice. "It all comes from getting to know people, learning their capabilities, and having faith in them. It's the same as what makes a marriage last."

## Scrubber chemistry for Texas Utilities Generating Co.

Texas Utilities Generating Co. (Tugco) counts itself diligent in seeking benefit from EPRI research, according to John Martin, Tugco vice president. But the effort took a new turn in 1981, when Martin was manager of technical services for the company's lignite-fired plants. At that time he and EPRI's Yeager began a series of occasional meetings to acquaint Martin's staff more closely with the projects of Yeager's CCS division.

Those meetings continue today, but the scope of interaction grew dramatically in 1984, when Tugco reorganized to include all generating plants of its parent company—lignite-fired, gas-fired, and nuclear. At that time also, Tugco's advanced engineering group took responsibility for structured technical exchanges with EPRI. R&D awareness and knowledgeability increased accordingly. "Any time we established a technical task force," says Martin, "there was an R&D representative who eventually would ask, 'Where is EPRI on this matter?'"

The upshot has been that several Tugco plants (among them Martin Lake, Big Brown, and Monticello) have hosted EPRI research efforts or have been the locale of cosponsored projects on turbine blades, generator reliability, baghouse and wet scrubber performance, and boiler erosion. For example, research aimed at developing a computer model for troubleshooting scrubber chemistry problems called for several representative plants, and Tugco's Martin Lake was one of those put forward in 1983.

EPRI's goal was to identify and solve operating problems, at the same time to define them in generic terms that a model could manipulate. Martin Lake exhibited three important examples, and subsequent analysis by EPRI's contractor yielded potential solutions, which were undertaken by Tugco in 1984 and 1985. "The three problems were absorber scaling, poor limestone utilization, and mist eliminator scaling," says Dorothy Stewart, a project manager in EPRI's Desulfurization Program. "We had seen them in other scrubbers, but different design and operating conditions meant that the causes, and therefore the solutions, could be different here."

Radian Corp., EPRI's research contractor, traced the absorber scaling partly to excessive oxidation of sulfite and lack of seed crystals for gypsum, which together force gypsum to precipitate on the absorber packing and surfaces. Unreacted limestone, a result of poor reagent use, also contributed to scale in both the absorber and the mist eliminator.

"The solutions, like the problems, were interconnected," reports Stewart. "Our contractor recommended recycling some gypsum crystals from the quencher to the absorber to head off scaling and plugging in the packing." Other points were to grind the limestone to a finer particle size, to split the feed between the quencher and the absorber, and to control both feed rates by means of pH. Changes in the wash water quality, wash sequence, and nozzles were also recommended for the mist eliminator.

Test operations at the Martin Lake plant proved all the researchers' recommendations, thereby validating the findings for use in EPRI's model. More to the point for Tugco, the changes are seen to be worth more than $2 million annually in reduced O&M costs at Martin Lake. "Perhaps better than $3 million," projects Stewart, "plus another $500,000 saving in reagent costs."

Those estimates are particularly impressive because they came only a short time after Tugco had failed in its effort to get a rate increase on the basis, in part, of rising O&M costs. Martin offers a good-natured justification for Tugco's joint efforts with EPRI that is consistent with that failure: "We cooperate because we're selfish. It's a very powerful motive."

## The R&D product line

Individual utility transactions are a powerful way to focus CCS technical aid and an obvious context for reviewing it. In each of the foregoing examples, a single utility asks one or more questions that result in one or more exchanges of communication with the CCS division and sometimes in research projects. But there are other, narrowly defined transactions where the research area itself is the matter of greater interest.

These are the application projects for new products of CCS research. Here, according to Manfred, the main ingredient is a completed development (it may have been demonstrated on its own or in the course of other work) that lacks utility-documented use in a working situation.

"Very few research results move on to the next logical stage," he says, "for all the good and usual reasons. The trouble is, this means that some successful developments are unused, when the next logical stage would be commercial practice. The problems are mostly communications lapses or errors in marketing," he adds, "but the point is that the right people don't hear about them."

Manfred and Piulle, representing the two technical departments of the CCS division, are coordinating a methodical effort to be sure that the right people do hear. Their inventory is represented by a large and still-growing decimal-numbered list, backed up by a pair of informal reference catalogs. Their principal communications medium is the division's small field organization, previously specializing in research facility and project management but now frankly soliciting application opportunities.

Billy McKinney in Chattanooga, Tennessee, Clark Harrison in Homer City, Pennsylvania (at EPRI's Coal Cleaning Test Facility), and Louis Rettenmaier in Denver, Colorado (at the Arapahoe Test Facility), have major responsibility. As Manfred puts it, "They are the people to call with inquiries about technical cooperation. They can't do all the applications, but they're the traffic cops who will make sure we do."

Compilation of the CCS division product list has been aided by the various research review meetings organized for SRP, PP&L, and others. The products have gained wide visibility in the course of meetings with these and many other member utilities to search out instances of EPRI research application and assess their benefit—that is, the actual or potential return on the member's R&D dollar.

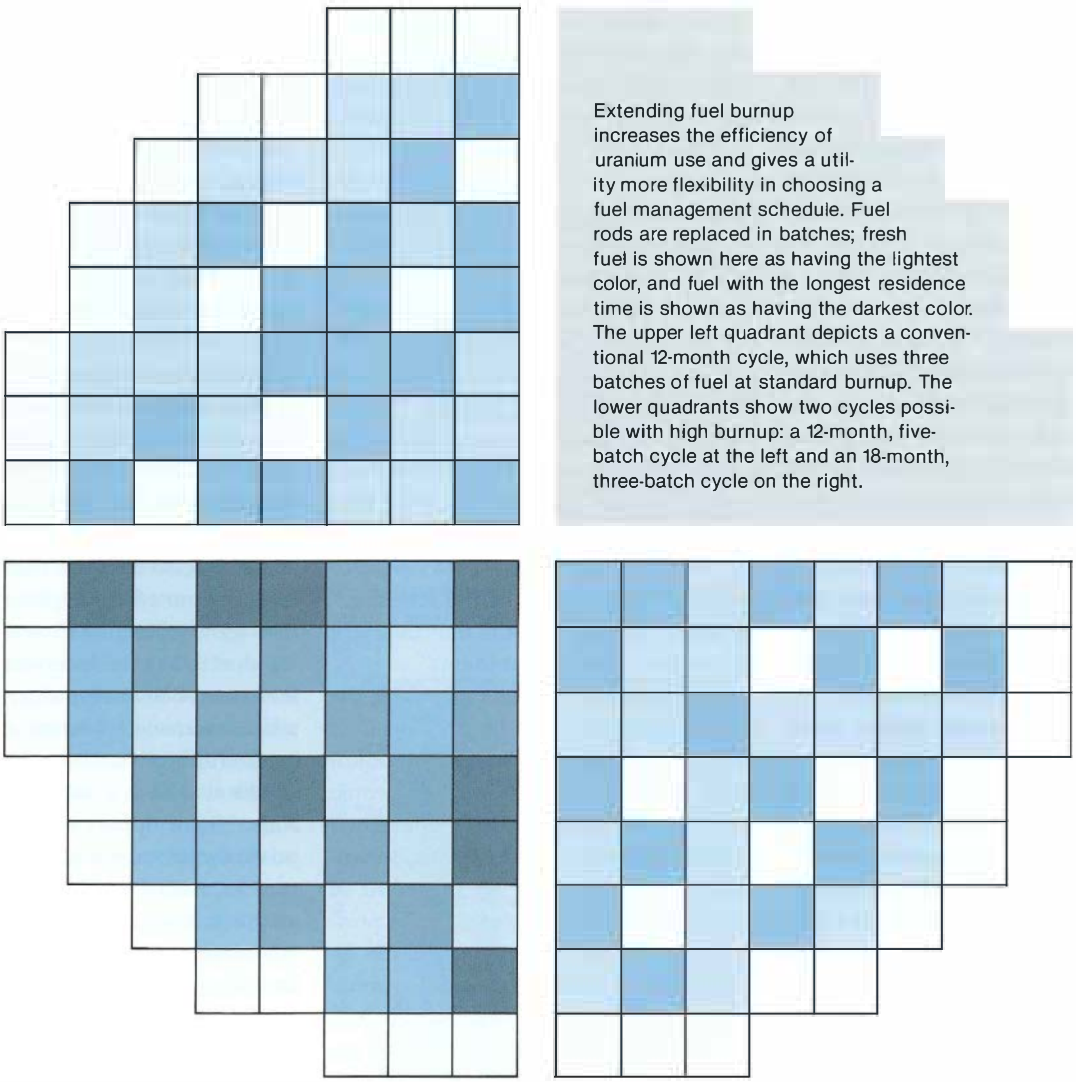
With their easily managed scope and modest cost, utility application projects are seen increasingly as a way to put the industry's final authenticating stamp on hundreds of successful R&D outcomes that do not make it into an industry supplier's commercial product line.

Does all this extensive one-to-one interchange square with the CCS division's primary responsibility to plan and manage R&D? Yeager clearly believes it does, in part because the CCS charter calls for so much "near-term problem solving, whose effectiveness is measurable only through immediate application." But he sees the problem of time allocation. "If we don't do our technical work well, there won't be any product to apply. So, when we answer the phone, we have to be careful how much we bite off.

"We also have to be selective," Yeager adds. "Some opportunities aren't appropriate for us, not a good use of our resources, nor of the industry's. As a part of the industry ourselves, we have to know when to say no and how to do it tactfully. There have been occasions," he concludes, "when we've steered somebody in another direction. We must, if we're going to maintain our own." ■

This story was written by Ralph Whitaker, feature editor. Technical background information was provided by Robert Carr, Stuart Dalton, Barry Dooley, Rolf Manfred, John Scheibel, and Dorothy Stewart of the Coal Combustion Systems Division.

# Designing Fuel Rods for High Burnup



Extending fuel burnup increases the efficiency of uranium use and gives a utility more flexibility in choosing a fuel management schedule. Fuel rods are replaced in batches; fresh fuel is shown here as having the lightest color, and fuel with the longest residence time is shown as having the darkest color. The upper left quadrant depicts a conventional 12-month cycle, which uses three batches of fuel at standard burnup. The lower quadrants show two cycles possible with high burnup: a 12-month, five-batch cycle at the left and an 18-month, three-batch cycle on the right.

**By the 1990s extended burnup of nuclear fuels is expected to be saving the utility industry several hundred million dollars each year.**

As the reliability of nuclear fuels improved during the early 1970s, electric utilities began to weigh the economic benefits of extending the burnup of these fuels, that is, increasing the amount of energy produced per unit weight of uranium dioxide in each fuel rod before it is removed from a reactor. Such a move to improve the efficiency of uranium use was considered a normal part of nuclear technology evolution. At the time there was no compelling reason to accelerate research on high-burnup fuels, however, because both government policy and industry planning were based on the assumption that spent fuel would be reprocessed and the unburned fissile material recovered. Then, in 1977, the Carter administration deferred indefinitely the reprocessing of nuclear fuels, and the electric utility industry was suddenly confronted with the need to use uranium more efficiently in a once-through fuel cycle.

The deferral policy meant that storage requirements for spent fuel would have to be expanded substantially and that as much as 20–30% more uranium and enrichment might be required to produce each kilowatthour of electricity than would be the case with recycle. Research showed that the most promising near-term way to minimize fuel-cycle costs in a once-through cycle was to increase fuel burnup, which can be accomplished by adjusting the power level of individual fuel rods and the length of time each rod remains in the reactor.

A recent survey of 15 EPRI member utilities, conducted by The S. M. Stoller Corp., indicates that an increase in burnup from 33 to 50 gigawatt-days per metric ton of uranium (GWd/tU) can result in a 4–8% saving in fuel cycle costs for pressurized water reactors (PWRs). For boiling water reactors (BWRs) the saving comes to 6–9% when the burnup is increased from 26 to 39 GWd/tU.

Higher burnup reduces fuel cycle costs by lowering the amount of uranium mining, milling, and enrichment required to produce new fuel, as well as requiring less transportation and shorter storage of spent fuel rods. It can also help utilities to lengthen the time between plant shutdowns for refueling from 12 months, the current standard, to up to 18 months or more. Longer refueling cycles have the potential advantage of providing higher plant availability, lower maintenance costs, and reduced radiation exposure of utility personnel.

Before utilities could subject the fuel rods in their reactors to higher burnup levels, however, extensive research was needed to determine the behavior of high-burnup fuels, ensure their safety, provide data for licensing, and demonstrate their suitability for longer refueling cycles.

For the last several years, EPRI has been involved in a number of cooperative efforts aimed at establishing the viability of high-burnup nuclear fuels and providing the data utilities will need to support related licensing, design, and operation efforts. This cooperation has been in the form of close coordination with significant programs separately funded by DOE and through EPRI programs cost-shared with the Empire State Electric Energy Research Corp., nuclear fuel vendors, and several individual utilities.

Much of this research is now nearing completion, with strategies for extending fuel burnup already being commercially adopted in PWRs and currently being demonstrated in BWRs. Most of the work so far has focused on fuel pellets and rod assemblies of standard design, but some basic design modifications that may further improve the benefits of high-burnup fuels have also been tested. By the 1990s extensive use of high-burnup fuels is expected to be saving the electric utility industry several hundred million dollars each year.

### A question of reliability

From an operational point of view, nuclear fuels differ from those of conventional power plants in two major respects: (1) they are loaded periodically, rather than being fed continuously into a plant, and (2) exquisite care must be taken to isolate the highly radioactive byproducts of the nuclear reaction. Because of these two conditions, pellets of uranium are hermetically sealed in corrosion-resistant Zircaloy tubes. A reactor contains tens of thousands of these fuel rods, which are clustered into mechanically connected assemblies. In a typical BWR, assemblies have an $8 \times 8$ arrangement of fuel rods; in PWRs, the arrangement is $14 \times 14$, or higher.

During refueling, fuel assemblies are replaced in batches, which typically represent about one-third of the rods in a core. The usual practice has been to replace the batch of most depleted rods each 12 months. Initially, fuels were designed to produce about 33 GWd/tU for PWRs and about 28 GWd/tU for BWRs. The goal of EPRI's recent research in this area has been to demonstrate that these burnup figures can be increased to 50 and 40 GWd/tU, respectively.

Whether extended burnup can be achieved is basically a question of reliability: will the Zircaloy cladding of fuel rods remain intact through more-intense periods of radiation exposure? During the early 1970s the answer to this question would probably have been no, because cladding failures that resulted from a variety of causes were preventing the fuel rods in many reactors from reaching even their design levels of burnup. Some of these problems were brought under control through operational changes, such as raising the power level of a reactor more slowly during startup and reducing the maximum power output of each rod. These operational changes also usually reduced the capacity factor of a reactor, however, so beginning in 1974 EPRI joined others in the nuclear fuel industry in an ambitious program of materials research to improve nuclear fuel reliability while boosting reactor operating efficiency.

After the critical change in government policy on reprocessing, the focus of EPRI's nuclear fuel research shifted toward showing that the recent improvements in fuel performance could be extended to higher burnup levels. Several areas of concern received emphasis.

*Fission gas release.* When a uranium nucleus splits, various fission products are released, some of which are such gases as xenon and krypton. At sufficiently high temperatures, these so-called fission gases can migrate through a fuel pellet and enter the gap that separates the pellets from the surrounding metal tube. The presence of these gases not only increases the internal pressure of a fuel rod but also reduces the thermal conductivity of the pellet-cladding gap. In extreme cases, this loss of conductivity could raise the temperature of a rod enough to accelerate the release of more fission gases, thus causing the internal temperature to increase even more rapidly—a process called thermal feedback. An important issue for research, therefore, was to determine the release of fission gases at high burnup and to make sure that increases in fuel rod temperature and pressure were both predictable and well within safe limits.

*Pellet stress.* Fission products and temperature-induced mechanical stresses in fuel pellets result in densification (from the shrinkage of microscopic internal voids), swelling, and relocation of fuel pellet material (from pellet cracking). Each of these, in turn, can produce strains in the surrounding Zircaloy cladding, whose integrity must be ensured. Another aim of research was thus to determine the extent of pellet deformation at high burnup and its effect on cladding stresses.

*Creep.* Permanent deformations in fuel rod cladding (creep) can result from the high external pressure in a water-cooled reactor and from interactions with the pellets inside. Predicting fuel performance requires an understanding of creep at high burnup levels.

*Corrosion.* Although Zircaloy was chosen as a fuel cladding partly because of its resistance to corrosion, slow oxidation caused by constant contact with hot water does occur in a reactor. The extent of corrosion at high burnup must be determined to prevent penetration of the cladding or buildup of an oxide layer thick enough to thermally insulate a rod and cause it to overheat.

*Rod growth and bowing.* Some physical interaction between pellets and cladding is unavoidable, and this can result in axial growth of fuel rods. Excessive growth can push a rod against its supports and cause the cladding to bow. Excessive bowing can distort the flow of coolant and create potential hot spots. Data are needed on both these phenomena at high burnup.

*Assembly stability.* If insertion and removal of fuel rods are to go smoothly, the mechanical supports holding together a rod assembly must also remain intact. Another aim of the high-burnup fuels research was to determine the extent of additional mechanical stress and corrosion on the fuel assemblies.

#### Testing higher burnup

To resolve these issues and provide utilities with the data they require for licensing high-burnup fuels, test fuel assemblies had to be inserted into operating commercial reactors and then examined both destructively and nondestructively. Such testing has now been conducted at nuclear power plants of several utilities in a coordinated research effort, working individually with fuel vendors and then sharing the information gathered. EPRI's research has included work with Combustion Engineering, Inc., on PWRs of Baltimore Gas & Electric Co. and Arkansas Power & Light Co.; with General Electric Co. on BWRs of Commonwealth Edison Co. and Philadelphia Electric Co.; and with Westinghouse Electric Corp. on PWRs of Commonwealth Edison Co. and Portland General Electric Co.

The first of these projects to be completed involved the tests at the Calvert Cliffs-1 reactor of Baltimore Gas & Electric, and a final report was published earlier this year. The work involved both destructive and nondestructive evaluation of 60 test fuel rods evenly distributed among three $14 \times 14$ assemblies irradiated to burnups of up to 54 GWd/tU. Five fuel types were used, which included variations in enrichment, pellet geometry, fuel density, and fuel microstructure. Helium at three pressure levels was added to each test rod.

From this work (which covered more than 10 years of fuel fabrication, testing, and evaluation) has emerged an extremely important and clear-cut conclusion. According to the final report, "No abrupt or unanticipated changes as a result of high-burnup operation were identified in any of the performance areas investigated." In other words, the reliability of standard $14 \times 14$ PWR fuels has been confirmed at high burnup, and on the basis of the data produced, in September NRC approved the extension of licensed burnup in these fuels to 52 GWd/tU.

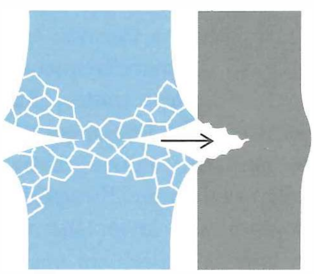
Several of the specific results of research at Calvert Cliffs have particular significance for resolving key technical issues. The rate of fission gas release, for example, did not accelerate during burnups up to 54 GWd/tU, and prepressurization with helium helped minimize the thermal feedback effect. By experimenting with pellets that had different microstructures, researchers concluded that volume changes and mechanical stress could be controlled by tailoring grain size and porosity. Other dimensional changes in fuel rods, including creep, axial rod growth, and bowing, also appeared to be predictable and well controlled. Corrosion of fuel cladding was found to remain within safe limits at high burnup, and fuel assembly stability was also confirmed. Similar observations were made in tests on $15 \times 15$ PWR fuel assemblies at the Zion power plant of Commonwealth Edison and on $17 \times 17$ assemblies at the Trojan plant of Portland General Electric. The performance of $16 \times 16$ assemblies at the Arkansas Unit One-2 reactor was also found to be excellent by detailed nondestructive examinations.

Evaluation of high-burnup test rods in BWRs is still going on, but work to date is equally encouraging. One completed project involved tests on five 7×7 fuel assemblies at Commonwealth Edison's Quad Cities-1 reactor. This research, for which a final report was published last year, established basic performance data for standard BWR fuels carried to high burnup. These data are now being used as a benchmark for calculations of high-burnup fuel performance.

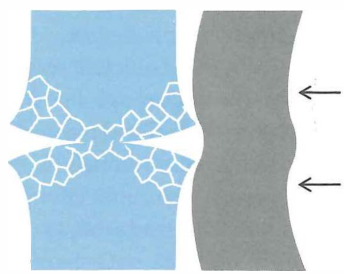
### Research Emphasis on Fuels for High Burnup

To show that nuclear fuels can withstand higher burnup levels without impaired safety or performance, several specific concerns had to be addressed. A decade of research has demonstrated the essential integrity of high-burnup fuels and provided data for predicting their performance in each of the areas of concern.

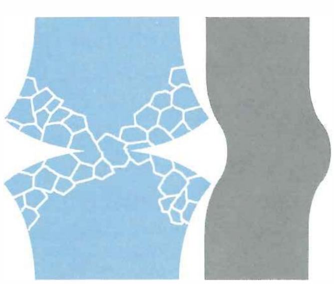
**Fission gas release.** Some fission products, such as xenon and krypton, are gases, whose presence can raise internal rod pressure and reduce thermal conductivity. Some of the fission products are chemically aggressive and, in conjunction with pellet stresses, can cause stress corrosion cracking of the Zircaloy.



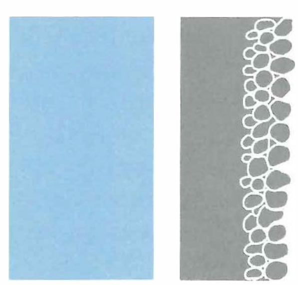
**Creep.** Pressure from water around fuel rods and from the expansion of fuel pellets inside can cause permanent deformations in cladding, known collectively as creep.



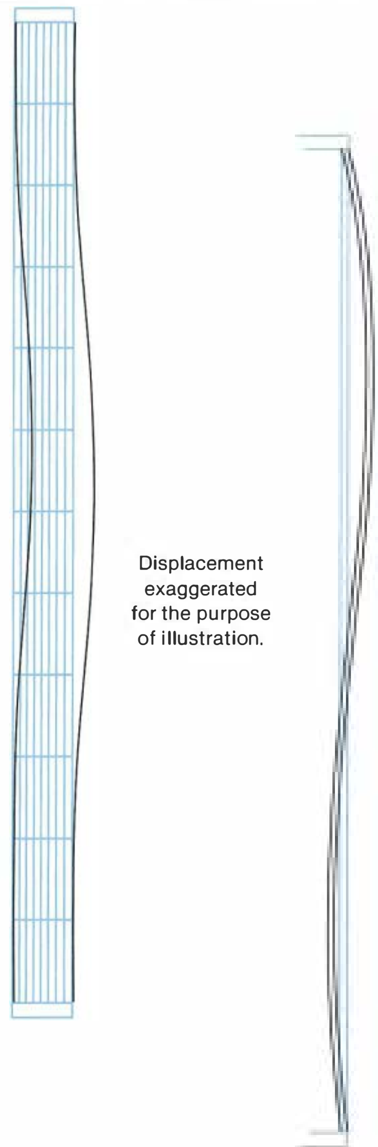
**Pellet stress.** Physical deformation of fuel pellets during operation can produce strains in the surrounding Zircaloy cladding.



**Corrosion.** Extending burnup results in increased Zircaloy corrosion, and data were needed to determine the increased buildup of the insulating oxide layer.



**Assembly stability.** Rods are mounted in mechanical assemblies, whose response during the longer in-reactor residence times typical of high burnup had to be determined.




**Rod growth and bowing.** Concern was expressed that extending fuel burnup levels might cause excessive axial growth and thus increase the propensity of the rods to bow.

Another major project on BWR fuel performance involves ongoing work at Philadelphia Electric's Peach Bottom nuclear power station. The aim of this project has been to evaluate four unpressurized 8×8 fuel assemblies irradiated to 40 GWd/tU and to compare their performance with that of a single assembly containing fuel rods pressurized with 3 atm (304 kPa) helium. The latest data available on these tests, published in December 1984, were taken at 35 GWd/tU for the unpressurized rods and at 32 GWd/tU for the pressurized rods. The interim results indicate that neither type of fuel rod experienced any threat to reliability at higher burnup but that the rods pressurized with helium showed less fission gas release. As in the case of PWR fuel rods, pressurizing the rod interiors with helium increased conduction of heat across the pellet-cladding gap, which resulted in a lower pellet temperature and thus reduced the release of fission gases.

"The research at these facilities definitely shows that fuel rods of both PWRs and BWRs are capable of extended burnup without loss of reliability," says Joseph Santucci, project manager. "From this work we have also learned some important ways to improve fuel design and to benchmark computer codes for making calculations related to licensing of high-burnup fuels."

### Utility benefits

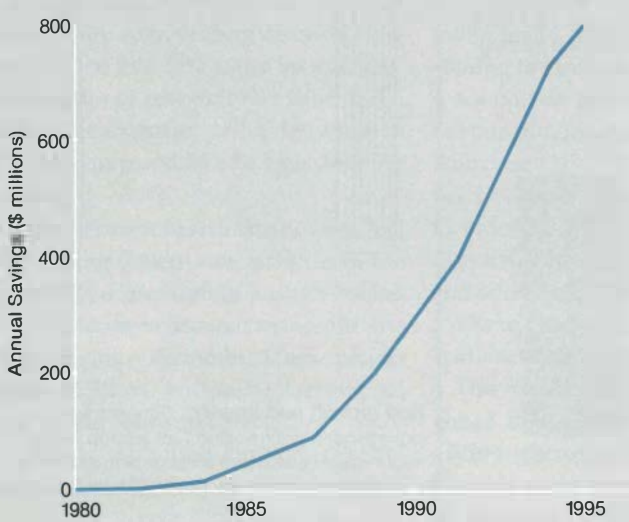
The best indication of how important the results of research on high-burnup fuels have been comes from a recent EPRI survey of utilities, which shows that 89% of PWR owners and 46% of BWR owners intend to shift to higher burnup levels. In addition to the immediate benefits of using uranium more efficiently, many of these utilities are also attracted by the additional flexibility they will have in choosing a refueling schedule.

In theory, the most efficient way to use uranium in a once-through cycle would be to feed in fresh fuel and remove spent fission products continuously. If such a scheme were possible, just enough uranium would be introduced to sustain fission, which would eliminate energy loss caused by neutron absorption in control materials (such as burnable poisons) and fission products. Conversely, the least efficient method would involve loading and unloading all the fuel at once, as a single batch of rods. This scheme would require the use of more control materials during the early part of the cycle, which would result in considerable energy loss. In BWRs, such control materials include gadolinium oxide added to pellets and boron carbide rods inserted into the reactor core. In PWRs, boron is added to the circulating water to minimize the need for burnable poisons, and additional rods of silver-indium-cadmium or other materials are also sometimes inserted.

In reality, nuclear reactors have fuel cycles that lie between the two extremes just described. The more frequently rods are changed, the less control materials are needed and the less energy is lost. On the other hand, frequent changes decrease plant availability. The question is, which option will lower the ultimate

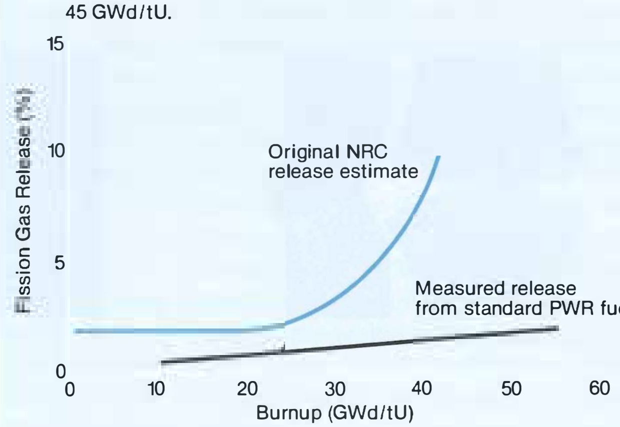
**Utility Industry Savings**

As a result of research on the high burnup of fuels, utilities should soon be saving hundreds of millions of dollars a year in fuel-cycle and operating costs. A recent survey of utilities revealed that 89% of PWR owners and 46% of BWR owners plan to extend fuel burnup in their reactors.




**Validating High Burnup of Fuels**

Before utilities could realize the benefits of extended burnup, the behavior of fuel rods at these burnup levels had to be established more precisely. Conservative assumptions used in earlier calculations, for example, indicated that fission gas release might rise precipitously at high burnup, but upper-bound fission gas release data collected during the recent research program showed that no such sudden change actually occurs. This sort of experimental validation is now allowing utilities to extend burnup levels for BWR fuels from the current average of 28.6 GWd/tU to a potential maximum of 36.5 GWd/tU and to extend levels for PWR fuels from 34.8 to 45 GWd/tU.



power generation costs for a particular utility? What high-burnup fuels do is allow utilities to choose between the fuel cost saving associated with shorter cycles and the operational advantages of longer cycles. Under the old PWR 12-month, three-batch cycle, individual fuel rods would reside in a reactor about 36 months. At an average burnup of 50 GWd/tU, PWR rods may reside up to 60 months, which, for example, can be divided into either 12-month, five-batch cycles or 18-month, three-batch cycles. Total fuel cycle costs would be less for the shorter cycle, but final power generation costs are generally less for the 18-month cycle.

The choice between these cycles will depend on a variety of utility-specific factors, including the cost of fuel, the availability of temporary storage for spent fuel, the cost of ultimate disposal, and the cost of plant downtime for refueling. In the United States it has been estimated that eliminating only three or four days a year of plant downtime by going to the 18-month fuel cycle would more than compensate for the added fuel cost involved. Because an 18-month refueling schedule should reduce downtime by as much as two weeks a year, American utilities are generally opting for the longer cycle. Some companies, however, may still choose to retain the 12-month cycle because of unique local conditions, such as sharp seasonal variations in load. (The annual cycle was originally chosen to allow utilities to refuel during periods of low demand.)

Perhaps the best indication of the actual saving that can be expected through a switch to high-burnup fuels used in an 18-month, three-batch cycle comes from recent analysis of data at the Calvert Cliffs plant. Baltimore Gas & Electric reports that the rate of discharge of spent fuels was decreased by about one-third, compared with the previous 12-month cycle, which greatly extended on-site storage capabilities. Total downtime and manpower costs were also reduced. The greatest cost saving resulted from decreased need for purchased replacement power during shutdown, which is now estimated to be about $10 million per year for the two reactors at the plant. The utility is considering further extension of its refueling schedule to 24 months in 1987, which is anticipated to produce an additional $5 million in annual savings.

"Utilities have necessarily approached the use of high-burnup fuels with considerable caution," says David Franklin, program manager. "EPRI's research in this area not only has demonstrated the feasibility of extending burnup but also is providing utilities with the data they need to choose between an 18-month and a 24-month refueling cycle."

### Future directions

Several ways of maximizing the benefits of high-burnup fuels are now being investigated. For example, one way to lower the operating temperature of high-burnup fuels, particularly in BWRs, is to increase the number of rods in each fuel assembly. EPRI is now sponsoring research to explore generic ways of achieving this goal. One solution to the problem is to increase the number of fuel rods in the fuel assembly by switching from an 8 × 8 configuration to a 9 × 9 pattern. Such a configuration reduces the linear heat generation rate of fuel rods by about 23%, increases the total heat transfer area exposed to water by about 10%, and also increases the moderation of neutrons by the water. Passage of neutrons through water slows them down in such a way that they are more likely to cause fission on impact with a uranium-235 nucleus, so increasing moderation is another way engineers improve uranium utilization. The 9 × 9 lattice also offers greater design flexibility—allowing, for example, the replacement of some fuel rods by water-filled rods to even out consumption of uranium-235 across an assembly.

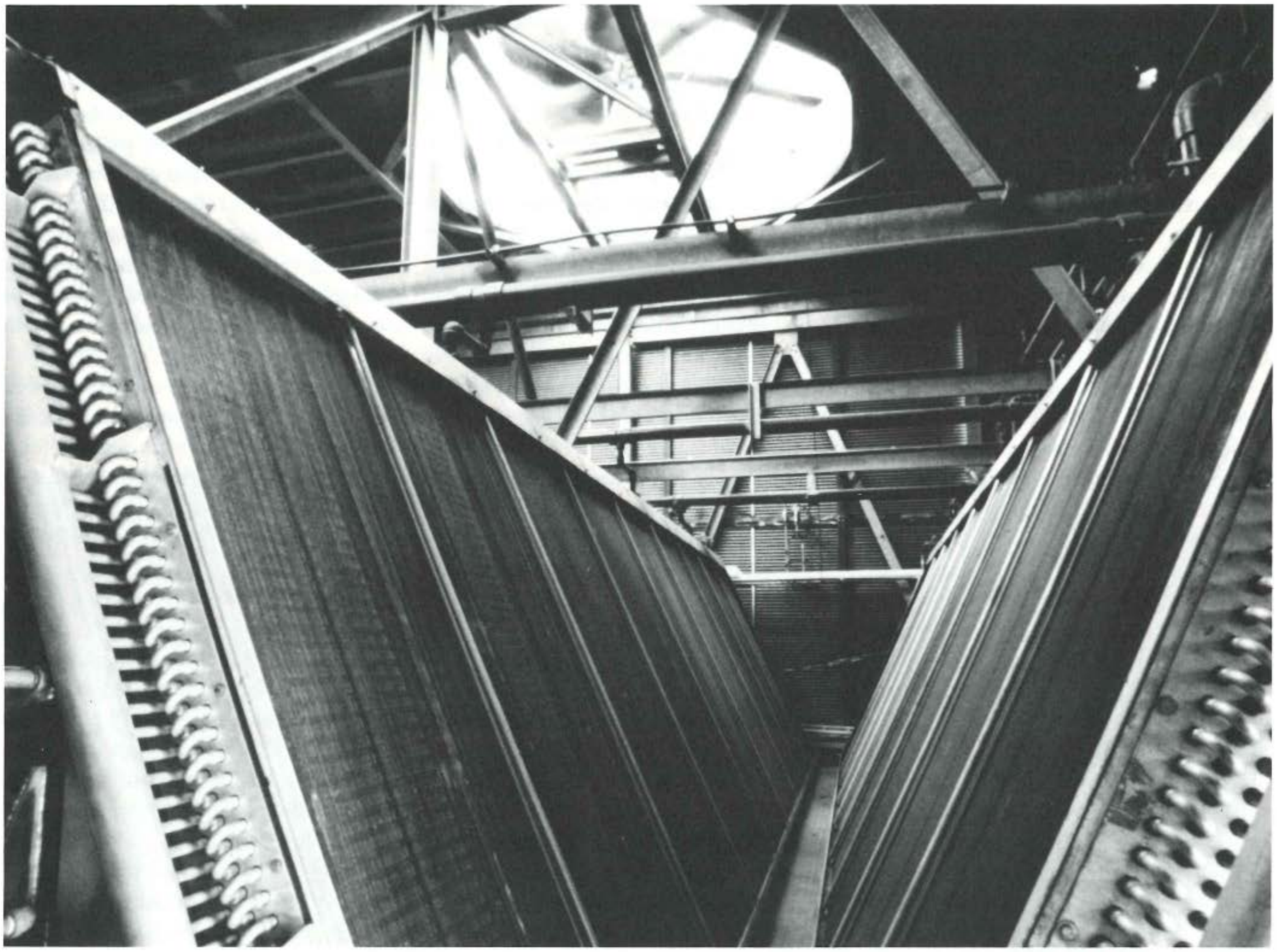
Exxon Nuclear Co., Inc., has used concepts demonstrated in this project to develop a prototype 9 × 9 fuel assembly. Four 9 × 9 demonstration fuel assemblies have been fabricated and inserted into Commonwealth Edison's Dresden-2 reactor for three 18-month cycles. The first of these cycles has now been completed and the results look quite promising. The current EPRI-sponsored research will provide vendors with generic information on 9 × 9 fuel assemblies, which they are then expected to optimize and provide commercially to utilities.

Another possible avenue to lower peak rod temperatures and increased uranium utilization in high-burnup fuels is to make changes in pellet design. EPRI has initiated a project to develop an understanding of how changes in basic pellet design may affect these fuel performance factors. Several concepts are being explored, including duplex pellets fabricated from two different enrichment levels and the use of distributed burnable poisons. If these concepts prove viable, the basic design information will be made available to fuel vendors for their use in developing and improving their current product lines.

"The high-burnup program has been quite successful," concludes Karl Stahlkopf, director of EPRI's Nuclear Systems and Materials Department, "in developing data to show that today's current commercial design fuels are capable of safe and reliable operation at high burnup levels. This capability allows a utility to choose the refueling outage length that best meets its operational and maintenance requirements. In addition, basic work aimed at lowering peak temperatures and increasing uranium utilization shows the promise of developing concepts that, when commercialized by nuclear fuel vendors, could extend burnup even further while increasing the reliability of the nuclear fuel." ■

This article was written by John Douglas, science writer. Technical background information was provided by David Franklin and Joseph Santucci, Nuclear Power Division.

# The Dry Look in Cooling Towers



Four years of operation at a host utility site have demonstrated the efficiency, economy, and safety of using an ammonia loop for condensing turbine exhaust steam in an indirect dry-cooling system.

More and more frequently in the years ahead, electric utilities that have to build new power plants will lack the water supplies needed for plant cooling. Water may be denied either by Mother Nature or by government allocation of an increasingly valuable resource. But regardless of whether the problem is outright scarcity or restricted availability, what then?

The hard answer is dry cooling, in which no water is consumed. Utilities everywhere in the United States have tried to avoid this option because of its high cost, but they are being drawn to consider it, either by itself or as the basis of so-called wet-dry systems. Such hybrids can be optimized for whatever limited water supply is available, using water only on the hottest days for peak cooling loads or only for some predetermined percentage of cooling load. Considering dry cooling alone, however, a commercial system today is about four times as expensive as an evaporative cooling system, its most likely conventional alternative in a given power plant design.

This sharp difference results from the nature of the dry and evaporative cooling processes. The heat sink for a dry-cooling system is the ambient air at its dry-bulb temperature—the true temperature of the air itself. The heat sink for an evaporative system is air at its wet-bulb temperature, a lower value that results when water is present, evaporating in the air and thereby absorbing energy from it. For dry cooling, therefore, the temperature floor of the entire process is higher.

Also, air is a far from ideal cooling medium—in many applications it performs as a thermal insulator. For both of these reasons, the main components of any dry-cooling system, its heat exchangers, are much larger and more expensive than those for wet cooling. The fixed costs for that portion of the power plant are therefore higher, and the operating costs are increased because of the lower thermal efficiency of the power cycle. As a result, electric energy from a dry-cooled plant may easily cost 5% more.

That differential has justified continuous research under EPRI sponsorship during the past 10 years. The principal objectives were to seek out and develop new dry-cooling technology that would perform better and cost less—that would offer greater thermal efficiency for the dollar. The research scope also called for pilot and demonstration plant operation to confirm these improvements, as well as to establish the safety and reliability of any new technology.

Culminating this R&D effort, EPRI's Coal Combustion Systems Division and a host utility, Pacific Gas and Electric Co., have for the last four years operated a 10-MW demonstration plant near Bakersfield, California. With cosponsorship by Southern California Edison Co., the Los Angeles Dept. of Water & Power, and the Salt River Project, EPRI and its contractors have evaluated three dry-cooling methods, all of which employ ammonia as an intermediate heat-rejection medium.

The project has thoroughly demonstrated both the performance efficiency and the operability of ammonia-based cooling technology for utility use. Subject to minor qualification, expectations for safety and reliability have been confirmed. The sponsors acknowledge that logging more hours of operation would bolster the record in these regards.

**Advanced dry cooling**

Generally, there are two types of dry cooling commercially available for power plant use: direct condensation and indirect cooling. In a direct-condensation system, steam exhausted from the turbine is condensed in coils that are exposed to the ambient air. The heat is rejected directly to the air. In an indirect-cooling system, exhaust steam is condensed by heat exchange with water flowing in a closed system. The heated water is then circulated through coils exposed to the air.

EPRI's project, called the Advanced Concepts Test (ACT), demonstrated systems based on indirect cooling. Ammonia was chosen (instead of water) because of at least two advantages. First, ammonia absorbs a large amount of energy per unit volume, and therefore heat exchangers, piping, and other equipment could be smaller than for a conventional dry-cooling installation of equal capacity.

This efficiency in heat exchange is particularly attractive at the boiling point. Ammonia absorbs about 100 times as much energy per unit volume as does water while vaporizing (at a constant temperature). The EPRI-sponsored system uses ammonia's change of phase across a negligible temperature range, instead of its cycling through a wide temperature range, as the heat-transfer mechanism.

Narrowing the overall temperature swing of the coolant in this fashion was the second advantage of using ammonia. The external ambient temperature (the heat sink) remained a fixed floor, but the steam-condensing temperature could be reduced. This in turn allowed a lower turbine exhaust steam pressure, thus extending the range of steam expansion and useful work in the turbine.

Ammonia's very low freezing point (−78°C) eliminates the wintertime concern in some regions that a cooling system will freeze. Also, ammonia is compatible with both steel and aluminum, the two most common system construction materials.

Altogether, the ammonia-based design was thermodynamically attractive, regaining some of the thermal efficiency and generation capacity losses suffered in water-based dry-cooling systems. The technology would still cost more than wet cooling, but it appeared to be the cheapest version of dry cooling.

The ACT project facility is at PG&E's Kern station, a 140-MW oil-fired power plant built in 1948; the plant has two units, rated at 60 and 80 MW, respectively. Each unit has an auxiliary turbine generator that produces energy for station use. One of these turbines was designated for the tests; it handles 60,000 lb/h (7.56 kg/s) of steam, the approximate equivalent of a 10-MW generating facility.

The Kern station was chosen also because its desert location ensures high temperatures—as high as 113°F (45°C). Held in cold standby status, the plant is operated only at times of peak demand. As a test bed, it offered a wide range of operating possibilities—startup, shutdown, cycling, and experiments with upsets and transients.

The main addition for the ACT project was the ammonia-based dry-cooling equipment. Four dry heat exchangers and 14 wet-dry exchangers, the principal components, are housed in a tower with four 16-ft-diameter (5-m) fans to expel hot air. ACT is highly instrumented so that research engineers can monitor test operations. Conditions can be recorded automatically as often as every 15 seconds for computer analysis.

As with conventional indirect dry cooling, ammonia-filled systems can be configured and operated in either a dry or a wet-dry mode. In the latter mode, water cooling is used to augment the capability of the dry system. Two of the ACT configurations are wet-dry; the third is all-dry.

### Three systems operated

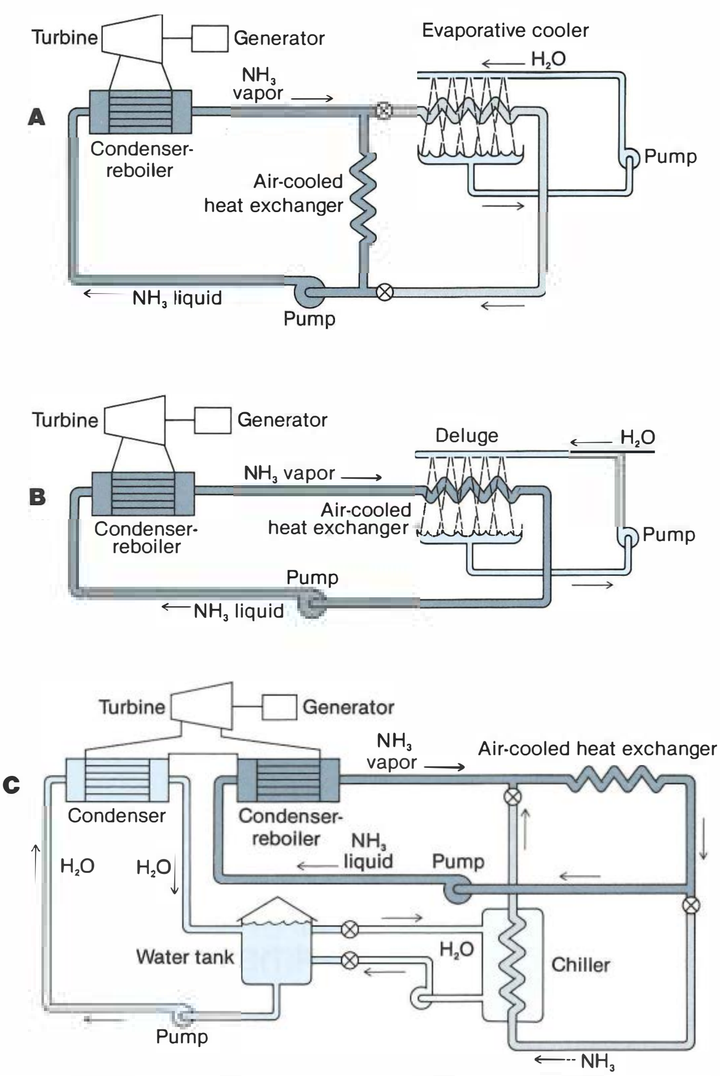
The first wet-dry configuration is an indirect-cooling system supplemented by an evaporative (wet) cooling tower alongside it. The dry heat exchanger handles most of the cooling load, transferring heat to rows of fins carved out of single blocks of aluminum; these fins present thousands of cooling surfaces to the air. On very hot days, when all-dry cooling is least efficient, some of the am-

**Three Ammonia-Based Systems**

Circulating between a condenser-reboiler and an air-cooled heat exchanger, a closed loop of ammonia is the principal element of three dry-cooling systems developed under EPRI sponsorship.

Two of the systems become wet-dry when supplemented by wet cooling. One of them, **A,** uses a small, separate evaporative cooler; the other, **B,** uses a shower of water (a "deluge") directly on the air-cooled heat exchanger.

Where supplemental water is out of the question at all times, a system with capacitive cooling, **C,** uses a closed loop of water as an extra heat sink during the day, then cools that water via heat exchange with the ammonia loop at night.



## WATER AS A COOLING MEDIUM

To appreciate the potential value of R&D in dry cooling, it helps to have some sense of the volume of water dry cooling replaces. Where water is used for dissipating the unusable heat produced in power generation, most of the plant water supply—from 75% to as much as 95%—is for this single purpose.

Until about 20 years ago, therefore, a power plant was usually built beside a river, lake, or ocean, from which water was pumped through the plant to absorb the heat. Little water is actually consumed in such a once-through system, but huge quantities are borrowed, warmed slightly, and then returned to the source. A typical steam electric plant may circulate as much as 500 gal/min ($3.15 \times 10^{-2}$ $m^3/s$) for every megawatt of capacity.

Two factors work against the use of once-through cooling: ecologic impacts (such as fish loss at the intake screens and higher temperature of the return flow) and the need for power plants far removed from large bodies of water. Utilities therefore turned to evaporative cooling, using natural- or forced-draft towers in which the cooling water itself is cooled by evaporation as it cascades down into a collection basin for reuse.

The volume of water circulating in an evaporative system is about the same as that in a comparably scaled once-through system, but the evaporative system is a continuous loop. Only makeup water is added, to counter the evaporation loss. That makeup fraction amounts to about 2% of the flow, however, or 10 gal/min ($6 \times 10^{-4}$ $m^3/s$) per megawatt. A 1000-MW coal-fired plant may use up 16,000 acre-feet ($19.7 \times 10^6$ $m^3$) a year, enough water to serve a city of 90,000.

Some 80% of today's new steam-electric plants are evaporatively cooled. By the year 2000, therefore, the daily volume of cooling-water consumption is likely to reach $10.5 \times 10^9$ gal ($39.7 \times 10^6$ $m^3$), eight times what it is today and 10% of the projected total national consumption. And water is already in short supply in some localities. Where water is plentiful it is also cheap, contributing only 1–3% to electricity cost. Utilities have been timely in acquiring and holding water rights, but where water is scarce, the new, waterless cooling technologies must be adopted. The problem is to minimize their greater cost. □

monia vapor is condensed in a heat exchanger by evaporating water.

The second wet-dry configuration also starts with an indirect-cooling system. But here the extra cooling capacity on hot days is achieved by spraying water over the fins of the dry heat exchanger—a mode of operation developed by Hungary's Hoterv Institute and known as a water deluge. Studies by Battelle, Pacific Northwest Laboratories, during the ACT project showed that the water used in the deluge mode can be less than 10% of what would be needed for an equivalent evaporative cooling tower, yet it can cut 20% off the dry-cooling increment of power production cost.

EPRI's all-dry cooling system on the ACT project is called capacitive cooling. The ammonia-filled indirect-cooling loop is paralleled by a water-filled loop, and turbine exhaust steam can be directed to one or both of the condensers as appropriate. The water loop features a large tank as a heat sink; the arrangement thus requires an initial charge of water, but it consumes none in operation.

This system normally uses only the ammonia loop, but on hot, high-demand days the water loop is added. Warm water (heated by the condensing steam) returns to the top of the tank and stratifies there, as in a domestic water heater. When the ambient temperature drops at night, the ammonia loop can again handle the entire cooling load. Water from the top of the tank is then pumped through a chiller, a heat exchanger in the ammonia loop, and its energy is thus rejected into the cool night air.

Key components of all three ACT systems are a steam condenser–ammonia reboiler and a phase separator; the latter is needed because the anhydrous (water-free) ammonia does not vaporize entirely as it condenses the turbine exhaust steam. The vapor component of the ammonia flows to the cooling tower, where it is condensed; the liquid fraction is combined with that condensed ammonia, and the total flow is then returned to the cooling loop.

Essentially, there is no sensible heating and cooling—that is, no temperature change—in the ammonia throughout this phase-change cycle, and the steam therefore condenses at a temperature closely approaching that of the ambient air. This near-match is also aided by design features of the condenser-reboiler. The ammonia side is called a porous boiling surface; it features minute cavities that encourage the formation of bubbles, thus expediting ammonia vaporization, enhancing heat transfer, minimizing the steam-ammonia temperature difference, and thereby helping to hold down the steam condensing temperature and improve the cycle efficiency.

Steam-side heat transfer is also enhanced, in this case by wire helically wound on the tubes. The presence of the wire influences the distribution of surface tension in the constantly forming layer of steam condensate, causing that layer to be thicker next to the wire but thinner everywhere else along the tube surface. The thin water layer offers less resistance to heat transfer, and the steam-ammonia temperature difference is further minimized. Features like these cut away at the economic penalties usually associated with dry cooling.

### ACT results

Operations at the ACT facility confirmed performance estimates and verified that ammonia is a safe and cost-effective medium for dry cooling. There was early concern as to whether ammonia could be handled safely in a power plant. Although it is a common industrial fluid, used as both a refrigerant and a fertilizer, ammonia is toxic and corrosive; and although it does not ignite readily, it will burn in air. "All the codes and standards for handling ammonia have long been established, however," explains John Bartz, EPRI's project manager, "so after reviewing a century of industrial experience, ACT researchers concluded that conventional ammonia-handling practices are suitable."

Still, conditions in power plants are demanding: the ACT demonstration was subject to its own startup problems and needed debugging. On one occasion, for example, an incorrect control sequence led to turbine overspeed and a shutoff of all electric power to the cooling system. There was no damage, and the occasion was thus a demonstration that the system accommodates and tolerates upset. Also, the standard ammonia circulating pumps operated unreliably at first, but this problem was traced to inadequate quality control in pump component fabrication and was largely overcome through more stringent quality control procedures. In the one incident where a considerable amount of ammonia was lost, by leakage past a gasket, there was no injury or plant damage.

Operating time for ACT was less than projected because the Kern station is on cold standby and is seldom dispatched. Moreover, because no redundancy was

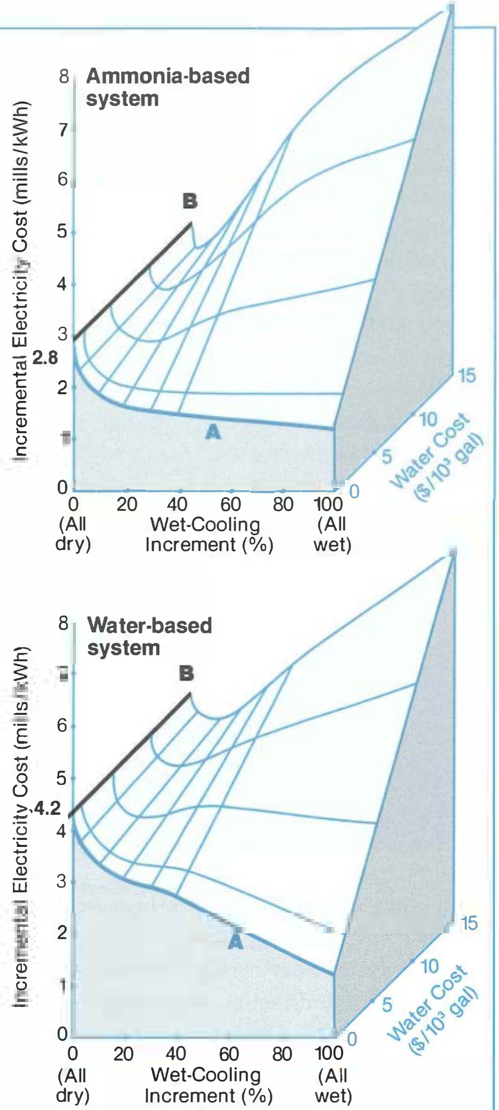
### Advantages of Ammonia

Three-dimensional graphs compare the incremental costs of electricity from power plants that use indirect dry cooling with ammonia (top) and with water (bottom). Sloping surfaces show how the cost varies when dry cooling is gradually replaced by wet (moving from left to right) and when the necessary water becomes more expensive (from front to back).

All-dry cooling is clearly cheaper with an ammonia-filled system (2.8 mills/kWh) than with a water-filled system (4.2 mills/kWh). And the ammonia system remains more economical even when 20–30% wet cooling is introduced at high water cost—as can be seen by comparing the lower elevations at the back of the graphs.

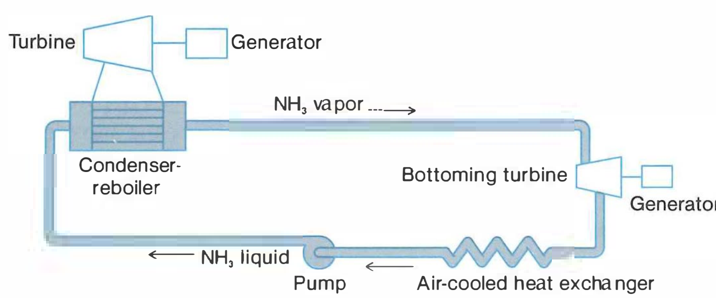
The important messages from these two graphs are that wet cooling is preferable whenever water is plentiful and cheap (low elevations in right foreground, indicated by *A*) and that a small substitution of wet cooling sharply reduces the overall cooling cost even when water is expensive (steep declines in elevation at left rear, indicated by *B*).

These incremental costs are over and above the base-case cost of electricity from a 500-MW plant (75% capacity factor) that uses once-through wet cooling.




### Coolant Vapor Drives Turbine

Ammonia's capacity (per unit volume) for heat exchange when it changes phase is the basis for using ammonia for indirect dry cooling. Its vapor phase can be further exploited by adding a small vapor turbine to the coolant loop, as in this system about to be tested by Electricité de France. Cost projections suggest that the energy from the bottoming turbine (about 25% of the overall output) will largely overcome the high cost of dry cooling.



provided in the demonstration systems, all operation ceased when any major component was examined, repaired, or modified. Nonetheless, the ACT project confirmed projections that the total costs of the ammonia system would be 35–50% less than those of current conventional dry-cooling systems.

In summary, the ammonia systems responded well to the operational fluctuations of the power plant. In addition, the overall performance of other components proved satisfactory; the air-cooled heat exchangers, for example, met or exceeded expectations.

The steam condenser–ammonia reboiler, on the other hand, did not perform as well as had been predicted by earlier bench-scale tests. The impact—on thermal performance and in turn on fuel economy—was an added 5% in total system costs; but Bartz sees this increment as minor in comparison with the 35–50% cost advantage projected for ammonia systems.

Each of the three tested cooling systems reveals advantages and disadvantages. The first wet-dry system (which uses supplemental evaporative cooling) has the advantage of avoiding corrosion or deposition on the main heat exchanger. The second wet-dry system (which includes periodic deluge) is attractive because it is very compact, but it is subject to deposition and corrosion from impurities in the deluge.

The capacitive cooling system (with its tank of temperature-cycled water) consumes no water and discharges none, but its economic advantages diminish very quickly if there is even a small supply of water available for either of the wet-dry modes.

### The future in question

Nominal completion of the ACT demonstration raises questions of its own. What is really the future prospect for commercial application of dry cooling? Individual utilities will come up with their own timetables for capacity expansion and potential need; for them the ACT demonstration documents an attractive new alternative. But the industry as a whole is not clamoring, and new dry-cooling technology is therefore best seen as a provision for the intermediate future, say 10 years ahead.

In the meantime, what remains to be done? Several design changes have been introduced at the ACT facility, and Bartz observes that others have been noted for use when another ammonia-cooled plant is built. For example, more extensive welded construction—instead of bolted assembly with gaskets—should essentially eliminate leakage of ammonia. Also, sloping the tubes in the air-cooled heat exchanger would promote drainage of condensed ammonia there and cut the likelihood of two-phase ammonia flow instability—"slugging" in the tubes.

Clearly, the newly attained state of the art already contrasts sharply with what was available only a few short years ago. Dry-cooling technology is neither as uncertain nor as high-priced, relative to current practice, as it formerly was.

What is still missing? If anything, it is the confidence that comes from long, uninterrupted (that is to say, uneventful) periods of plant operation. None of the ACT systems shows evidence of significant corrosion or fouling of heat exchanger surfaces or other components—at least not yet. But Bartz believes that more operating experience would be needed before firm conclusions could be drawn from the ACT facility. "Primarily," he says, "we would watch for corrosion of the deluge heat exchanger, and for fouling of the all-dry unit by airborne debris."

How can the desired experience and confidence be gained? The ACT facility is a question mark; after four years of demonstration operations there, the host utility's needs for its Kern station may be changing. Bartz and others of the R&D community are therefore looking at two promising projects outside the United States and laying plans to follow their operations closely.

One of these is near Calgary, Alberta, Canada, at a pipeline compressor station run by Nova Corporation, an Alberta pipeline firm; the other is near Paris, France, and is being put into operation by the national utility there, Electricité de France. Each installation includes a small ammonia-vapor turbine to augment overall power production.

The Canadian application involves a combustion turbine (fired by gas from the pipeline) used to drive a pipeline compressor. An ammonia cycle recovers heat from the turbine exhaust, and the vaporized ammonia drives a 5-MW turbine to augment the station's pumping power. The ammonia is finally condensed in an air-cooled heat exchanger, as in the indirect dry-cooling systems at the ACT facility.

The French demonstration by an electric utility is being watched more closely. It is a 20-MW facility; about 5 MW of that output comes from the ammonia turbine. The system seems particularly well suited to France because winter is the time of peak electricity demand there; summer air conditioning is not a major element of utility load. Thus, the output of the ammonia turbine during the winter (as well as the saving due to reduced system size) almost overcomes the higher cost of using a dry-cooling approach, and in summer the system has excess cooling capacity.

According to Bartz, a goal of the French is to build a 1300-MW nuclear plant with an ammonia bottoming cycle. Taken together, the R&D to reach that goal and the apparent cost-effectiveness of the secondary turbine are motivating close scrutiny of the Electricité de France project by researchers elsewhere. On these bases, it is evident that dry-cooling technology will continue to move toward the future. ■

This article was written by Joel Shurkin, science writer. Technical background information was provided by John Bartz and John Maulbetsch, Coal Combustion Systems Division.

## Cool Storage Handbook Guides HVAC Designers

The cool storage concept—shifting all or part of a building's air conditioning requirements to off-peak hours—offers businesses a way to reduce their peak electricity demand and their electricity bills. Now a state-of-the-art handbook is available to heating, ventilating, and air conditioning (HVAC) engineers who design ice and chilled-water storage systems for commercial buildings. Developed under EPRI contract, the *Commercial Cool Storage Design Guide* (EM-3891) provides comprehensive guidance for evaluating the cost-effectiveness of cool storage options; for selecting, configuring, and screening system alternatives; and for implementing and maintaining an HVAC system that incorporates cool storage. The handbook also discusses deviations from conventional HVAC design, describes common design errors, and presents two case studies illustrating successful cool storage applications. It contains other information of importance to HVAC engineers, including lists of HVAC manufacturers, trade organizations, and R&D firms. The guide is the second in a series of EPRI publications designed to disseminate commercial cool storage information; the first was the *Commercial Cool Storage Primer* (EM-3371), published in 1984. ■ *EPRI Contact: Veronika Rabl (415) 855-2401*

## Hand-Held Resonance Device Inspects Stator Coil Wedges

Increasingly, hydrogenerator failures have been traced to problems involving coil insulation damage caused by loose or improperly installed wedges in the stator slots. The traditional tap test used by inspectors to find loose wedges is time-consuming and sometimes unreliable. EPRI's research into ways to eliminate this type of failure has produced a prototype hand-held inspection device that is capable of electronically measuring the tightness of hydrogenerator stator coil wedges. Its development is based on variations in natural resonance parameters that can be expected from differences in wedge tightness. Properly tight wedges generally have a resonant frequency between 800 Hz and 1000 Hz; loose wedges show no resonance in this range; and jammed wedges, if they resonate at all, do so at lower amplitudes and frequencies. Thus, the instrument operates by shaking the wedges in a controlled mode and then monitoring the response. The portable unit, currently marketed by Vintek, Inc., allows plant personnel to quickly detect and replace loose or jammed stator wedges during maintenance or other planned outages. ■ *Contact: Vintek, Inc. (509) 375-1871; EPRI Contact: D. K. Sharma (415) 855-2302*

## Damaged Poles Repaired While in Service

Three companies—Loadmaster Systems, Inc., Ecom Systems, Inc., and Utilitech, Inc.—have recently executed licensing agreements with EPRI for an innovative tool called the helical driver, part of an EPRI-developed foundation construction system. The agreements permit the companies to supply the driver to utilities, furnish a service that uses driver equipment, or license other organizations to provide driver services in specific locations. By using the helical driver to repair and restore damaged wood poles, utilities can delay replacing the millions of poles that have deteriorated because of rot or decay. The beauty of the helical driver is that its steel casing is installed around an existing pole, which means that the work can be done while the line is energized. Because of its special shape, the casing evacuates the soil between it and the pole as it is driven into the ground. This makes it easier for repair personnel to apply fungicides or other rot-retardants and to backfill the annulus with grout or epoxy. The helical driver repair method not only delays pole replacement costs but also helps to strengthen existing poles. ■ *Contact: Loadmaster Systems, Inc. (602) 624-8809; Ecom Systems, Inc. (213) 727-9853; Utilitech, Inc. (415) 837-2419; EPRI Contact: Vito Longo (415) 855-2287*

## Information Exchange, R&D Help Niagara Mohawk Solve Face Seal Problem

Improved communication among utilities and a broad-based engineering effort initiated by EPRI have helped provide Niagara Mohawk Power Corp. with the solution to a problem that has long plagued nuclear power plant owners: the recurring failure of mechanical face seals. Face seal hardware and software studies contracted by EPRI in the early 1980s indicated that in addition to correcting design deficiencies, enhanced maintenance and operational techniques were needed to ensure reliable performance. An EPRI-hosted seminar brought Niagara Mohawk together with 16 other utilities and several manufacturers, consultants, and federal agencies to look at face seal problems in detail and to discuss their individual face seal R&D programs. The shared findings and seminar are paying off. Niagara Mohawk has instituted new precision dimensional controls on face seal parts in conjunction with other upgraded maintenance procedures. An advanced face seal development program is under way that could virtually eliminate pump face seal–related outages at the utility's Nine Mile Point power plant, potentially saving an estimated $742,000 annually. ■ *EPRI Contact: Floyd Gelhaus (415) 855-2024*

## Back-Pressure Measurement Method Improves Performance

A search for ways to improve the heat rate at the Clay Boswell station led Minnesota Power Co. engineers to investigate the effects of condenser cleanliness on load limitations. In carrying out the study, however, they found that determining heat rate proved difficult without a back-pressure measurement method that was both reliable and consistent. Drawing on pressure-monitoring techniques developed under EPRI contract, the engineers were able to design a system of pressure sensors that is expected to save the utility about $94,000 yearly in heat rate and fan efficiencies at the Clay Boswell station alone. The new measurement method involves carefully controlled sampling and computer averaging of pressure monitors. To eliminate the problematic variations in pressure readings caused by moisture collection, pressure readings are taken only after moisture is bled from the sensing lines. This new method has proved to be more accurate than older measurement techniques and will allow more efficient operation of the Clay Boswell unit. It also offers better guidance for operating cooling-tower fans. ■ *EPRI Contact: Frank Wong (415) 855-8969*

## New EPRI Manual Presents the Facts on Indoor Air Quality

Outdoor air pollution has long been a public concern, but only recently has the quality of indoor air become a subject of study. Incidences of poor indoor air quality have often been attributed to low air exchange rates resulting from the successful energy conservation measures undertaken by homeowners to combat rising energy costs. But current research suggests that such conservation measures—unless carried to the extreme—may have only an incremental effect on indoor air quality. Because the relationship of indoor air quality to air exchange and residential energy use is very complex, EPRI has developed the *Indoor Air Quality Manual* (EM-3469) to help electric utilities assist homeowners, builders, and new home buyers in understanding the many factors that affect indoor air quality. Concise and authoritative, the manual summarizes the link between pollutant concentrations, air exchange, and energy conservation and describes the characteristics and health effects of selected air pollutants. It also discusses current indoor air quality standards, monitoring and modeling methods, instrumentation, and pollutant control measures. Utility marketing and conservation personnel, energy management consultants, and consumer relations specialists will find this manual a useful reference. ■ *EPRI Contact: Arvo Lannus (415) 855-2398*

## FEATURE Code Offers In-House Rotordynamic Evaluation Capability

The complicated dynamic rotating systems in today's power plants often exhibit forced and self-excited vibrations. Although sophisticated techniques for analyzing and predicting these vibrations exist, those available to the utility industry have shown limited success, especially in coping with the problems of large steam turbine generators. Now a new software program developed under EPRI contract offers utilities an independent, in-house capability for diagnosing and correcting lateral vibrational problems in large rotor-bearing systems. This versatile program, called FEATURE, employs the finite-element method to develop matrices that describe the various properties of a rotor system. FEATURE can calculate linear critical speed, damped response, and stability for simple pumps and fans or extremely long coupled systems, such as large turbogenerator sets. The code is available for IBM machines or computers with a virtual memory operating system, and it is used in conjunction with COJOUR, an EPRI software program for solving problems in a variety of fluid film journal-bearing configurations. ■ *EPRI Contact: Stanley Pace (415) 855-2826*

# The Federal Commitment to Conservation and Renewables

DOE's assistant secretary–designate for conservation and renewable energy reviews the federal government's support of research programs in these technologies.

Donna R. Fitzpatrick was nominated last August by the president to be DOE assistant secretary for conservation and renewable energy. She has served as acting assistant secretary since March 1985 and was the principal deputy assistant secretary for over one year before that. A lawyer with an undergraduate degree in physics, Fitzpatrick also served on a consulting team that in 1983 conducted a general review of DOE's conservation and renewable energy programs for the secretary of energy.

**Which DOE program areas fall under your supervision?**

As my title indicates, I oversee the programs in energy efficiency and alternative fuels, which include energy conservation research for industry, buildings, and vehicles. The conservation programs have an annual budget of approximately $180 million. The programs in the renewable energy section involve research in active and passive solar, photovoltaics, solar-thermal, geothermal, wind, biomass, small-scale hydro, ocean energy, and municipal waste technologies. I also have responsibility for projects on electric energy systems and energy storage. The annual budget of the renewables programs is approximately $175 million, and the budget for energy storage and distribution is in the $30 million range. I like to think that these program areas define how we can better use energy for transportation, buildings, and industry; how we can efficiently transmit and store energy; and how we can take advantage of domestically available and abundant energy resources. These areas of research contribute to the overall goal of the department, which is to ensure that the nation has an adequate supply of energy at a reasonable cost.

**Can you give some examples of projects undertaken in the conservation program?**

We view energy conservation as a critical energy resource. I often use the comparison that the amount of energy saved through conservation and efficiency improvements in this country in the past 10 years is equivalent to four Alaskan pipelines. And energy conservation never runs dry.

We improve conservation by providing research on better building methods, materials, and designs and by working with building contractors to explain advances in building designs that bring energy savings. For example, research in the conservation program has yielded a computer-based data collection package that monitors and records electric energy consumption in commercial facilities. We are also studying the effect of increasing the level of thermal insulation in residences to achieve superinsulated houses. Current monitoring of such superinsulated houses has indicated that energy consumption can be reduced by approximately 50% in comparison with more conventional energy-efficient homes.

The Office of Building and Community Systems started a program to work closely with utilities on least-cost planning methods. We want to help transfer the experiences some utilities have had already in improved end-use efficiency and load management, which can help them avoid building new capacity while continuing to meet their growing demand. The DOE project offices sponsor workshops to explain the weatherization and conservation techniques we have developed and to encourage utilities to pursue these programs in their own service areas. Also, we are initiating pilot projects with a few utilities to help them determine the conservation potential in their regions.

We are committed to the idea that any conservation program must be locally developed because each utility service area is unique. The people who can best determine the most effective way to save energy in an area are the people who live there, not those of us here in Washington. We want to transfer our research knowledge to the utilities, but they have to initiate the programs—that is what we need to get across.

**What is the responsibility of the Office of State and Local Assistance Programs?**

This office works with utilities, industry, and consumers to encourage conservation. Specifically, the office, which was set up as a grant program by statute, administers programs that provide financial and technical assistance to a wide range of sectors to help them take advantage of effective conservation techniques and technologies. One of its programs focuses on assistance for low-income housing weatherization. Another supplies matching grants to schools and hospitals to help them conduct energy audits and install energy-efficient equipment. These grant programs are administered by the states.

Fitzpatrick

The low-income weatherization assistance program, with a budget of about $190 million, was set up to reduce residential consumption of heating oil and hot water and thereby reduce the nation's dependence on imported fuels. The states offer the grant money to local community assistance groups, who then go out and weatherize low-income housing by providing weather stripping, storm windows, and attic insulation. The other important aspect of this program is that when houses are made more energy efficient, low-income families pay less for energy and increase the income available for other essentials. More than 1.2 million homes have been weatherized through this program.

The program of grants to schools and hospitals is equally successful—we always run out of grant money before we run out of applicants. In this program, with a budget of approximately $48 million, the federal government meets half of the costs of energy efficiency improvements, a substantial savings to a school or hospital. The hospitals, in particular, are very interested in this program because of the specialized equipment, lighting, and temperature controls they require. Also, money that a hospital doesn't have to spend on energy can go back into improving services for the patients. I believe the program has already provided over 13,500 grants to community schools and hospitals, helping to improve over 37,000 buildings.

Two other programs of this office, the Energy Extension Service and the State Energy Conservation Program, provide states with information, training, and some financial assistance to encourage them to plan and implement energy efficiency improvements among groups they have identified as priority candidates for conservation.

One reason these local assistance programs are important is that they prove how much money can be saved through conservation techniques. We can document actual savings after weatherization and efficient equipment are installed in a building. If we can prove that in two years the owner will earn back all the money spent on these improvements, then we know that the program is going to succeed. So now we want schools and hospitals to start putting more of their own resources into this program. We also feel that utility companies should be supporting these types of improvements because conservation will help them manage their electrical load in the long run.

**What other research under the conservation program would interest utilities?**

Two programs come immediately to mind: heat pumps and electric vehicles.

In the Office of Industrial Programs, the Waste Energy Reduction Division is investigating both chemical and mechanical heat pumps in an attempt to broaden their industrial applications through improved efficiency and higher temperature ranges. And the Building Equipment Division is investigating high-efficiency residential heat pumps, although most of this research is directed at thermally activated heat pumps. We know now that large industrial heat pumps do work and can be highly efficient, but their cost must be brought down before they can move successfully into industry. Not only must they be low cost; they also need to be relatively maintenance free.

The Office of Transportation Systems is studying vehicle propulsion technology, electric and hybrid vehicle technology, advanced ceramic materials, and alternative fuels. The office is researching nickel-iron and gel cell lead-acid batteries for electric vehicle applications. DOE has already participated in tests of over 680 electric vehicles throughout the country, involving more than 3 million miles of operation. In fact, I was in Detroit this fall to dedicate a new electric van that General Motors has designed and built, which will be used by Detroit Edison Co. and several other utilities in fleet operations. Using these vehicles in fleets at utilities provides a good testing ground for them—the data are reliable and easily obtained. Electric vehicles can act as load levelers for a utility because they are recharged at night.

The procedure for the heat pump and electric vehicle programs, as well as for virtually all other DOE programs, is to plan the research along with the industry that will be using the developed product. We don't want to get started on research that is not going to be used once it is completed; therefore, industry involvement is a requirement. As a result, we also do not usually initiate a project unless industry is willing to share costs with us. We want to be sure there is a vested interest in the project, so that when the federal government's role is finished, the appropriate industry will continue with the research. A good example is a joint project we entered into with EPRI this year to develop an electric van to be competitive in performance and cost with conventional service vans. The research will cover the design, fabrication, and in-service evaluation of this electric van.

**What research is DOE undertaking in the solar technologies?**

Research is under way on virtually all aspects of renewable energy: passive and active solar, solar-thermal, photovoltaics, biomass, geothermal, wind, ocean-thermal, and hydropower. I will just touch on a few of the utility-related projects.

DOE and several utilities are cosponsoring a pilot 10-MW central receiver project in Barstow, California, which involves 80 acres of heliostats that focus sunlight at extremely high concentration levels on a receiver mounted at the top of a tower. Water circulates through the receiver, absorbing and transferring heat to produce electricity through a conventional steam cycle. This facility is being operated by Southern California Edison Co. We are also exploring, again with support from industry and EPRI, a molten-salt solar electric experiment at the Central Receiver Test Facility in Albuquerque, New Mexico. This project will determine whether it is economic to use molten nitrate salts as the working and storage fluid in a solar-thermal central receiver system for electric power generation.

In cooperation with Georgia Power Co., we are supporting the Shenandoah project at Newman, Georgia, which involves a distributed solar receiver system that uses parabolic dish modules. The 114 dish receivers direct the sun's heat to a silicone-based transfer fluid, which takes the energy to a central location. There the heat is used to produce electricity and steam to drive an absorption-cycle air conditioner for a nearby knitwear factory owned by Bleyle of America, Inc.

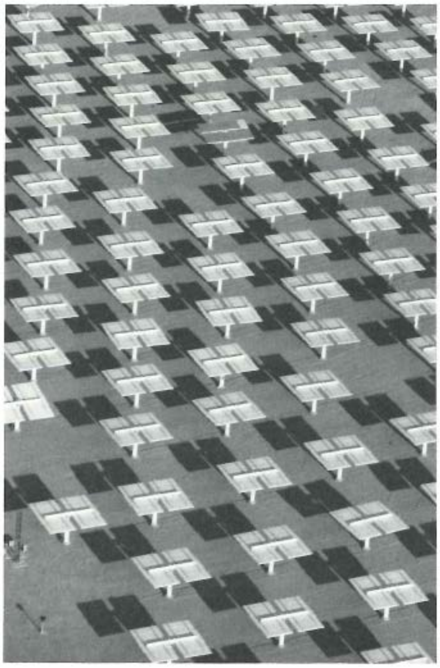
DOE has also had a long cooperative association with the nation's electric utilities in the development of wind energy technology. We have collaborated with EPRI and utilities—including Pacific Gas and Electric Co., the Bonneville Power Administration, and Southern California Edison Co.—in evaluating experimental wind turbines and exchanging data from our respective research facilities. With the initial success of the private sector in bringing wind technology to the marketplace, we have begun to explore the exchange of field performance data with utilities and manufacturers; the goal is to achieve technology advances to improve wind machine performance while developing practical definitions of equipment reliability and durability.

**Is there government support for geothermal research?**

Oh yes. In fact, we have another joint project with EPRI to install and test a 1-MW hybrid power system at a geopressured well, a type of geothermal resource mostly found along the Gulf Coast. There is potential for three types of energy from geopressured wells—thermal energy from hot water, chemical energy from methane dissolved in this water, and mechanical energy from the pressure found in the well. If it is possible to retrieve all this energy economically, the technology should have a great future.

We are also cooperating with EPRI, the state of California, four utilities, and two private developers in the design, construction, and evaluation of the Heber

Solar-thermal heliostats



Active/passive solar home


ctric vehicle

Experimental wind turbine

Heber geothermal plant

Low-cost weatherization

binary-cycle geothermal power plant in the Imperial Valley of California. By means of an organic working fluid, this binary-cycle plant will enable heat from lower-temperature geothermal brines to be used to drive a turbine. The Heber generator, the world's first large-scale generator of its kind, has been constructed and is currently undergoing operational testing under the management of San Diego Gas & Electric Co. A great deal of valuable information has already been gained from the Heber plant. It is our view that as this project progresses, it will improve the understanding of both utility personnel and energy researchers of the potential of this important domestic resource.

The reason we are committed to projects like Heber and the geopressured well research is that the nation needs to explore these new domestic technologies to lessen our dependence on foreign fuels. The federal government is the appropriate source for these long-term, high-risk projects. It is difficult for a private company to invest in research that doesn't bring immediate results. And the government, of course, is able to take more risks in research than a private company.

**What are some of the research developments in electric energy systems and energy storage?**

The Office of Energy Storage and Distribution is looking at large batteries for storing off-peak energy (both the zinc bromide and sodium-sulfur batteries), chemical and hydrogen systems for advanced electrochemical concepts, and underground energy storage. Also, the office's Electric Energy Systems Section is involved in three areas of research important to the utility industry: HVDC and underground cable transmission; reliability, including electromagnetic pulse (EMP) impacts; and electric field effects.

The research into the effects of an EMP caused by a high-altitude nuclear explosion is a good example of appropriate research for the federal government. DOE is the only organization looking into this problem as it relates to the civilian power grid. The Department of Defense is investigating EMP effects on military communications systems, and we of course share information. We hope to be able to assess the magnitude and shape of transient voltages appearing on power systems and to evaluate the impact of such transients on the integrity of electrical equipment.

Research into electric field effects is being conducted at Battelle, Pacific Northwest Laboratories. The objective of this research is to determine the biologic effects of exposure to fields produced by high-voltage electric power transmission lines, and it should also provide a comprehensive methodology for carrying out human health risk assessment. It is important for DOE to be involved in research of this kind because the government can provide information to gain public acceptance for the use of these lines. We closely coordinate all our research efforts with what is being undertaken by EPRI on behalf of the industry.

**How do you get the results of your research out to interested industries and the general public?**

That is always a problem, trying to transfer technology. By maintaining close contact with industry through all the stages of a research project, we can keep each other pretty well informed. We also sponsor various workshops and seminars to discuss research progress and to get advice on new directions. For example, the Office of Energy Storage and Distribution sponsored a workshop this past October in cooperation with utilities to assess what utility systems will look like 20 to 25 years from now, and to determine what research is needed to prepare for any changes that might occur. The same office also held a joint workshop in November with EPRI and the state of New York on research on the biologic effects of high-voltage lines. I think that our cooperation with industry is very strong, and to enhance these important contacts, we are reorganizing to create a technology transfer office. The specific task of this office will be to work with each of the program areas to best determine how to get information out to those who can use it, whether it be industry researchers, manufacturers, or the general public.

DOE also maintains two telephone services for anyone with questions on conservation and renewable energy research or on appropriate technology. These services are very direct ways to get up-to-date information to interested consumers. The first, the Conservation and Renewable Energy Inquiry and Referral Service (CAREIRS), can handle any questions related to using, installing, or understanding conservation and solar energy techniques. Last year over 40,000 inquiries were handled by this service, resulting in the distribution of over 155,000 publications. CAREIRS can be reached by these toll-free numbers: in the continental United States (except Pennsylvania), 800-523-2929; in Pennsylvania, 800-462-4983; in Alaska and Hawaii, 800-523-4700.

The second service is the National Appropriate Technology Assistance Service (NATAS), which addresses questions about energy-related appropriate technologies. We find that most NATAS users are homeowners or renters, small businesses, state and local governments, and institutions. The specialists at the service provide callers with information on low-cost, environmentally sound, locally based approaches to energy problems that help consumers help themselves. NATAS can be reached by these toll-free numbers: in all states except Montana, 800-428-2525; in Montana, 800-428-1718.

**Finally, what do you see as the federal government's goal in pursuing conservation and renewable energy research?**

It is rather simply what I stated before as the goal for all of our programs: to be certain there is an adequate supply of energy at a reasonable cost. What we mean by adequate is that the limiting factor in economic growth and activity should not be the availability of energy, and that energy supply should not be a controlling factor in our foreign policy.

The feeling today is that there is no longer an energy crisis. World oil production is up, and the price per barrel may fall again. Consumers have seen prices level out at the gas pump so they believe the situation is in hand, but that perception is a problem. There are many ways to continue to save energy through conservation, and the public must be reminded of that.

I would also like to take the other position and say that there never really was an energy crisis because we really have so much energy available to us. We just need to be smarter about how we use it. That's why using our own domestic resources—such as coal and nuclear and, when economic, renewable resources—together with proven conservation techniques makes the most sense. We had a petroleum crisis, not an energy crisis, and we still have a petroleum habit. One of our goals here is to help cure the nation of that habit. ■

This article was written by Christine Lawrence, Washington Office.

# EPRI and DOE Launch Electric Van Design Project

Commercial fleet vans are being pursued as the most likely near-term application for electric vehicles.

EPRI has entered a joint project with DOE and its contractor, EG&G Idaho, Inc., to develop an electric van that is expected to be competitive with conventional service vans in terms of performance and life-cycle cost. Begun late this summer, the multiyear effort will include the design, fabrication, and field evaluation of an improved electric van. The finished van is expected to serve as a prototype for commercial fleet electric vehicles (EVs) that could be produced in limited quantities by 1987 or 1988.

David Douglas, EPRI program manager, notes that service fleets present an especially promising application for the coming generation of electric vehicles. Because EVs require regular recharging, they are well suited to the short, planned routes and regular schedules followed by fleet vans.

In a related project EPRI is providing support to the Electric Vehicle Development Corp. (EVDC) of Cupertino, California, to evaluate an existing electric van, the General Motors Co. Griffon. Individual utilities, General Motors, and other private corporations are involved in the EVDC market application development project.

In the current phase of the EPRI–DOE project, 31 Griffons have been purchased for evaluation in the service fleets of one Canadian and six U.S. utilities. Evaluation is expected to establish the acceptability of EVs for fleet applications, generate ideas for product improvements, and initiate a General Motors infrastructure for EV service and support.

Recently intensified EPRI research includes projects on improved battery and propulsion systems for EVs. Already under way is a project with Gould, Inc., and DOE's Argonne National Laboratory that by 1987 is expected to yield a prototype lithium-sulfide battery and substantially increase EV acceleration and range. Another effort targeted for completion in 1987 is being funded by EPRI at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California. It is expected to produce a new, sealed lead-acid battery that will reduce requirements for battery watering, a major cost item affecting the ownership and operation of EVs today.

EPRI-supported researchers at JPL are also at work on ac drive propulsion systems for EVs. These systems use state-of-the-art transistors to convert the battery's current from dc to ac, thus allowing for a lighter, smaller ac drive train that will increase vehicle efficiency and performance. An additional EPRI assessment study is exploring the potential of hybrid EVs, which combine electric motors and internal combustion systems.

"Technical improvement has brought EVs to the brink of being competitive for fleet service applications," Douglas says. "By the middle of the next decade, EVs should also be competitive for many kinds of personal use. The heightened thrust of EPRI's EV research is part of this rapid progress and is an outgrowth of a recognition of the potential value of EVs to utilities and to society as a whole."

Public acceptance of EVs is expected to

aid efforts at fuel conservation and environmental protection and provide utilities with a major source of off-peak load and revenue. For more information about EPRI's EV research, contact David Douglas, Energy Management and Utilization Division (415) 855-2887. ■

## Lignite Sample Successfully Cleaned

Preliminary tests at EPRI's Coal Cleaning Test Facility (CCTF) indicate that some low-sulfur lignite coal can be cleaned successfully. This summer a 20-ton sample of East Texas lignite was run through a short coal-cleaning test after having been crushed. The purpose of the test was to gauge how responsive the small lignite particles (fines) would be to cleaning. Clark Harrison, CCTF manager, notes that the lignite fines in this sample went through the system as well as some bituminous coals.

These early tests also refute the assumption that lignite, after being crushed and mixed with water, would turn into a sludge that would clog coal-cleaning circuits. Further, it was found that cleaning the fines reduced ash content by 41% and sulfur content by 31%. Cleaning also increased the lignite's heating value by 6% while retaining almost 80% of its energy content. Although the tests on the fines were not designed as rigorous scientific studies, they provide encouraging signs that some lignite fines can be successfully cleaned. A full CCTF test program is under way to determine the extent to which lignite can be improved by crushing and cleaning.

Available locally to many utilities, lignite is relatively inexpensive and low in sulfur, two qualities that make it an attractive coal to burn. Its disadvantages have been that it has low fuel value and may contain petrified wood, clay, or sand, which cause boiler tube erosion and other power plant problems.

In an effort to make lignite a more practical coal source, Texas Utilities Co., a major U.S. coal producer and consumer, undertook CCTF tests after demonstration and commercial-scale tests with Dow Chemical Co. indicated that coarse lignite is responsive to gravity separation. If it is proved that most lignite can be cleaned economically, there will be considerable benefit not only to utilities now burning this so-called dirty coal but also to utilities looking for additional fuel options.

Utilities interested in learning more about the lignite tests or in providing their coals for future CCTF tests should contact Clark Harrison at the Coal Cleaning Test Facility (412) 479-3503. ■

## Lake Liming Appears Effective

Early reports of fish activity appear encouraging to scientists involved in the EPRI-funded $3 million lake acidification mitigation project (LAMP) under way in upstate New York. The activity indicates that calcium carbonate is very effective in neutralizing lake acidity and promoting fish habitats. The four-year LAMP study is taking place on three privately owned lakes in a region of the Adirondacks Mountains, where some 200 small lakes are too acidic for fish survival.

In late spring of this year, brook trout were planted in two lakes that had been treated four days earlier with calcium carbonate. Both lakes were acidic prior to treatment, and fish populations could not be sustained. The lakes did, however, contain algae, insects, and small organisms on which fish feed. Within a day, the planted trout were breaking water and actively feeding. After two weeks of observation, the trout were continuing to feed actively and showed no sign of leaving the lakes, which fish planted before the liming had done.

Marketed under the name Nautex SL, the very pure, finely ground calcium carbonate neutralizer is chemically similar to the crushed agricultural limestone that has been used for many years to counteract excessive acidity in soil and water. Farmers, for example, use crushed limestone to neutralize their acidic soils.

Prepared in a water slurry, Nautex SL is applied to a lake, where it dissolves rapidly. Its small particle size is an advantage because the material does not fall to the bottom, where it could become inactive. With the dissolution, the water's acidity is lowered to create a lake that is no longer acidic. The lime also adds carbonate, which buffers against rapid changes in acidity, and calcium, which may protect the fishery against metal toxicity.

In the LAMP project a helicopter was used to spray the slurry onto the water in a carefully designed pattern. Thirty-five tons of the material were applied to 60-acre Woods Lake, and 11 tons to 12-acre Cranberry Pond. Several days later, the waters were stocked with trout, all tagged to enable scientists to study their subsequent activity.

Lake liming is among a number of options considered for the rapid recovery of acidified lakes. Results of recent liming projects in Sweden, Norway, Canada, and other areas of the United States show that acidity is decreased and trout survival is improved by this mitigative technique. In fact, ponds have been limed in New York since the late 1950s in efforts to maintain trout populations. Prior to the LAMP study, however, little extensive research had been done on liming.

LAMP, designed to fill this void, is an integrated physical, chemical, and biologic study of the effects of lake liming, and the work will include an evaluation of liming as a tool for protecting, re-storing, and managing freshwater fisheries. One important factor is that lakes differ widely in the rate at which they exchange water (or flush). For those that flush rapidly, an operational liming program would call for periodic reliming. Because the lakes in the LAMP study fall in this category, researchers expect them to reacidify within one to two years. Thus the researchers will follow and record the lakes' water chemistry and biology over the next two or three years to study their reacidification rates and other related processes.

The LAMP research team includes the General Research Corp. and nine principal investigators from five organizations: Clarkson College, Cornell University, the University of Indiana, Syracuse University, and International Science and Technology, Inc. The U.S. Geological Survey, under subcontract to Cornell, is performing stream and groundwater measurements. The International Paper Co., owner of the lakes involved in the study, granted permission for their liming.

For further information, contact Donald Porcella, EPRI project manager, Energy Analysis and Environment Division (415) 855-2723. ■

## EPRI, European Group Agree to Exchange LMFBR Information

An exchange agreement between EPRI and the German-Dutch-Belgian utility consortium, SBK, marks EPRI's second major overseas collaboration this past year on liquid metal fast breeder reactor (LMFBR) research. An earlier agreement, with Japan's Central Research Institute of the Electric Power Industry, concentrates on developmental LMFBR technology.

EPRI's agreement with SBK (which stands for Schnellbrüter-Kernkraftwerkgesellschaft, or fast breeder nuclear power plant company) focuses on sharing LMFBR information in such key areas as nuclear safety, design requirements and features, economics, R&D, and startup and operating experience. A major aspect of the agreement calls for an EPRI or U.S. utility employee to participate in the startup and operation of SBK's SNR-300, a 300-MW (e) loop-type demonstration plant located in Kalkar, near the city of Essen in the Federal Republic of Germany. Construction of SNR-300 is nearly complete, and the plant is expected to be fully operational by the end of 1986.

U.S. utilities are expecting to gain valuable technical knowledge and experience about a modern LMFBR demonstration plant from this on-site cooperative venture. In return, SBK utility personnel are invited to the operating fast flux test facility (FFTF) near Richland, Washington, for the purpose of sharing plant operating data. A companion agreement between EPRI and DOE arranges for EPRI to channel information from FFTF to SBK in exchange for information from SBK and SNR-300.

SBK is directing the West German utility effort on LMFBRs in cooperation with utilities from Belgium and The Netherlands. For more information about the EPRI–SBK agreement, contact Clark Gibbs, director of EPRI's Advanced Nuclear Generation Department (312) 961-4161. ■

## CALENDAR

For additional information on the EPRI-sponsored/cosponsored meetings listed below, please contact the person indicated.

### FEBRUARY

**4–5**
**3d Symposium: Integrated Environmental Control**
Pittsburgh, Pennsylvania
Contact: Edward Cichanowicz (415) 855-2374

**9–11**
**8th Annual Workshop: Radwaste**
Savannah, Georgia
Contact: Patricia Robinson (415) 855-2412

**12–14**
**Symposium: Advances in Fossil Fuel Power Plant Water Cycling**
Orlando, Florida
Contact: Wayne Micheletti (415) 855-2469

**18–20**
**Hydro O&M Workshop and Seminar: Life Extension**
San Francisco, California
Contact: James Birk (415) 855-2562

**25–28**
**6th Symposium: Transfer and Utilization of Particulate Control Technology**
New Orleans, Louisiana
Contact: Ralph Altman (615) 899-0072

### MARCH

**17–19**
**Hydro O&M Workshop and Seminar: Life Extension**
Washington, D.C.
Contact: James Birk (415) 855-2562

**18–20**
**Steam Turbine Blading**
Los Angeles, California
Contact: Thomas McCloskey (415) 855-2655

**19–21**
**PWR Primary Water Chemistry and Radiation Field Control**
Oakland, California
Contact: Christopher Wood (415) 855-2379

### MAY

**13–14**
**Reducing Cobalt in Nuclear Plant Materials**
Seattle, Washington
Contact: Howard Ocken (415) 855-2055

### JUNE

**2–4**
**Conference: Life Extension and Assessment of Fossil Fuel Power Plants**
Washington, D.C.
Contact: Barry Dooley (415) 855-2458

# R&D Status Report
# ADVANCED POWER SYSTEMS DIVISION

Dwain Spencer, Vice President

## IGCC PHASED CAPACITY ADDITION

*The concept of matching electrical load growth with small capacity additions is receiving increasing attention in today's environment of highly uncertain load growth. Because electricity demand cannot be forecast with a high degree of reliability, strong incentives exist both to reduce the portion of a utility's construction-related capital that is outstanding or at risk and to maintain the flexibility to rapidly respond to unpredicted changes in load growth. These objectives can be accomplished through the addition of capacity in small increments that match the more predictable, near-term increases in electrical load. Paralleling load in this manner poses new challenges, however, because small capacity increments are typically characterized by high unit cost and low efficiency. Ongoing evaluations by EPRI and a number of utilities are beginning to suggest that integrated gasification–combined-cycle (IGCC) plants offer an attractive solution to this apparent dilemma.*

Because of their highly modular nature, IGCC plants lend themselves naturally to phased construction; as a result, the associated diseconomies of small scale can be minimized. An additional flexibility offered by these plants is the ability to respond rapidly to unpredicted accelerations in load growth. In one phased IGCC capacity addition scenario under study, for example, the first increment of capacity can be put into service in the relatively short time required to obtain permits for and install a combustion turbine.

There are two other ways in which the phased addition of IGCC plants tends to reduce a utility's risk and offer increased flexibility. First, by phasing IGCC capacity additions, a utility can take advantage of the current, relatively depressed prices for distillate oil and natural gas in the early phases without committing to a long-term dependence on premium fuels. Second, a utility can respond to more stringent environmental legislation in the design of IGCC plants without a large increase in plant capital cost and with only a negligible impact in terms of technical risk.

### IGCC scenarios

Although the modularity of IGCC plants suggests that diseconomies of scale can be minimized, the magnitude of the scale penalties had not been quantified until EPRI contracted with Fluor Engineers, Inc., to identify the plant performance and cost implications of phased IGCC addition (RP2029-13).

Many scenarios of phased IGCC plant construction are conceivable, and the relative economic merits of these options cannot be determined a priori. From among the many options EPRI, together with more than 10 utilities, developed 10 cases that address the IGCC phasing alternatives of greatest interest to the participants. The 10 scenarios fall into two categories: those differing from one another in the sequence of phased capacity addition and those differing in gasification plant design parameters. The five cases that represent unique phasing scenarios are as follows.

- Unphased IGCC plant
- Phased IGCC plant in which two phases of advanced-combustion-turbine installations are followed by a third phase consisting of a gasification plant and a steam bottoming cycle
- Phased IGCC plant similar to the second scenario but with the addition of a separate combined-cycle phase prior to the operation of the gasification plant
- Phased IGCC plant in which three phases of current-technology combustion turbine installations are followed by a fourth phase that converts this capacity to an IGCC
- Phased IGCC plant in which two advanced-combustion-turbine phases are followed by a third phase consisting of a gasification plant and a steam cycle that makes use of existing, 20- to 30-year-old steam turbines

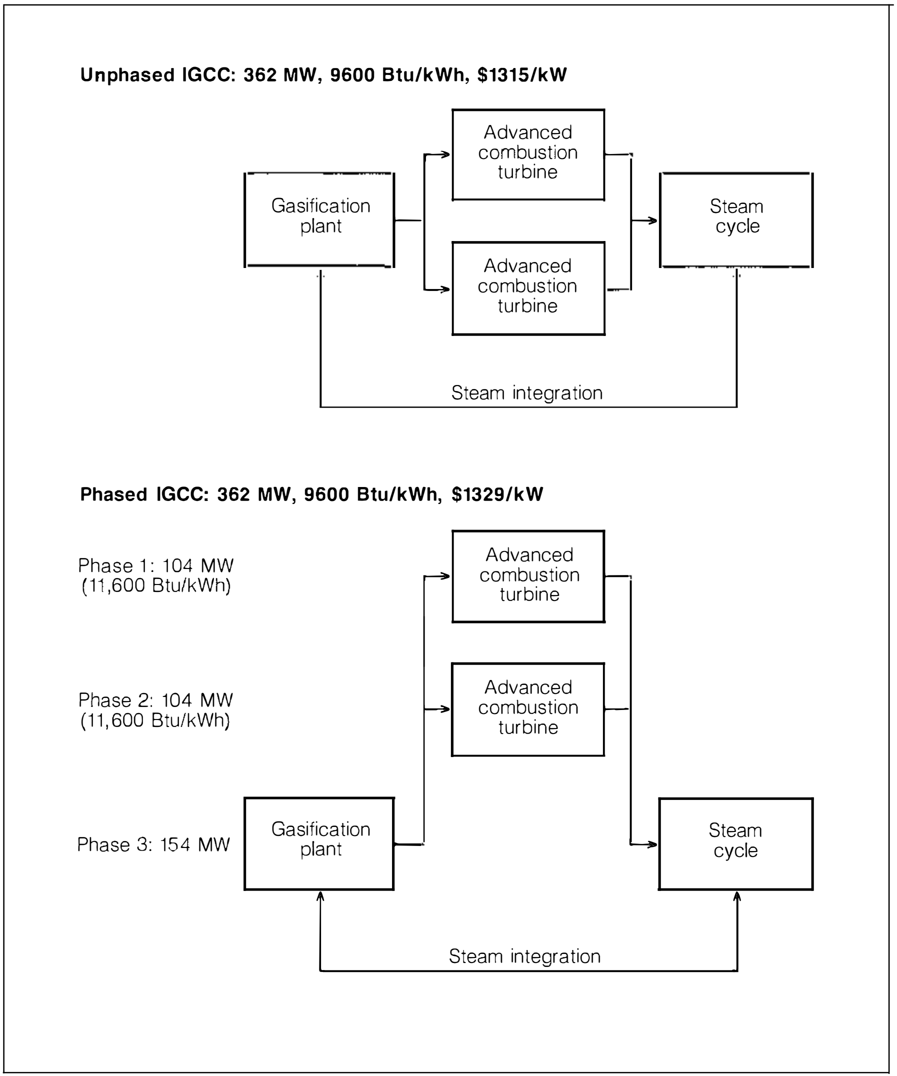
Each of these five scenarios is based on a single set of design options. For example, the gasification technology employed in each case is the Texaco process with radiant syngas cooling followed by a gas quench. The gasification plant in each scenario is designed to load the combustion turbines with fuel at the high ambient temperature of 88°F (31°C), and the design coal is Illinois No. 6. With the exception of one scenario, all the plants are designed around an advanced combustion turbine having a 2200°F (1205°C) rotor inlet temperature and resembling the near-commercial General Electric Co. machine. All plants are designed to surpass New Source Performance Standards for $NO_x$, $SO_x$, and particulate emissions.

### Performance and capital cost estimates

To illustrate the project approach, we will focus on Fluor's evaluation of the first two IGCC phasing scenarios (Figure 1). Note that when completed, the phased plant is identical to the unphased plant in terms of capacity (362 MW) and heat rate (9600 Btu/kWh). Thus, in this type of phasing sequence, there are no performance penalties associated with matching load with small capacity increments. Fluor's estimates on plant facilities investment are $1329/kW for the phased plant and $1315/kW for the unphased plant (January 1984 dollars). The small penalty associated with phasing—only $14/kW—confirms the expectation that the modular nature of IGCC plants renders them well suited to phased capacity addition.

Matching load with small capacity increments, as in the phased IGCC plant scenario, allows for the deferral of capital expenditures. Although deferring these expenditures reduces the present value of fixed-charge costs to the utility, in this case the saving is accomplished through the addition of capacity that is initially fueled by distillate oil or natural gas. Because these fuels are more costly than coal, one would expect that the present value of production costs (fuel costs and operating and maintenance costs) would be higher for the phased scenario. In order to properly compare

Figure 1 Performance and cost estimates were developed for two examples of IGCC capacity addition: an unphased plant (i.e., a plant built all at one time) and a phased plant constructed and put into service in three increments. The results suggest that IGCC plants may enable utilities to realize the flexibility and other benefits of phased capacity addition without incurring a performance penalty or a large increase in capital cost. (Costs are in January 1984 dollars; interim plant heat rates, based on distillate fuel, are given for phases 1 and 2 of the phased IGCC.)




the economic merits of the two alternatives depicted in Figure 1, the operation of each scenario was simulated with a production costing model, and the results were then combined with those from a fixed-charge analysis.

## Economic analysis

Two approaches are now being used in the economic analysis of the phasing scenarios evaluated by Fluor. EPRI, through Zaininger Engineering Co., is performing generation expansion analyses that employ typical coal- and oil-based utility systems as backdrops for the installation of the new IGCC capacity (RP2699-4). In addition, the 10 utilities that have participated in guiding the Fluor work are now in the process of performing economic analyses based on their own production costing models, financial criteria, and load projections.

According to initial reports from this utility effort, the economic analysis has proved to be somewhat more problematical than originally anticipated. Because certain IGCC characteristics represent a departure from more conventional units, most existing production costing models cannot accurately represent the operation of these plants. Some examples of characteristics that are challenging to model are the highly modular nature of IGCC plants, their ability to use natural gas (or distillate oil) as a backup fuel to the coal gas, and their ambient-temperature-dependent performance characteristics.

Through the use of simplifying assumptions, many of the utility participants have been able to approximate the operation of the IGCC plants in their production costing simulations. The preliminary conclusion drawn by a number of these utilities is that phased IGCC capacity addition could be an economically and strategically attractive new generation option. In fact, Potomac Electric Power Co., one of the participants in this study, recently announced tentative plans to place a phased IGCC plant into service in the mid 1990s. The decision was based on the attractive results of the company's pioneering economic analysis of phased IGCC capacity addition.

The objectives of the more generalized economic analysis being performed for EPRI by Zaininger are to assess the relative merits of the 10 phasing scenarios evaluated by Fluor and to isolate and quantify the impacts of various utility-specific characteristics on the economic efficacy of phased IGCC capacity addition. At the time of this writing, preliminary results for only the two scenarios depicted in Figure 1 were available.

A hypothetical 4000-MW utility system served as the backdrop for the EPRI economic analysis; 85% of this system was coal-fired capacity, and the remainder was oil-fired. An annual 2.5% system load growth was used as the basis for the addition of new capacity. The approach taken by Zaininger was to substitute an IGCC plant for a new 362-MW conventional coal-fired plant in the expansion plan of the 4000-MW coal-based system. In one case the substituted generation capacity was the 362-MW unphased IGCC plant. In another case it was the phased IGCC plant, whose three phases were assumed to be installed at even, one-year intervals. By substituting only one plant in each scenario, the analysts were able to isolate the impact of the capacity addition and to avoid the compounding effects of multiple substitutions.

Fuel costs and financial criteria for the analysis were based on the 1985 EPRI *Technical Assessment Guide* (TAG), as were data on the new 362-MW conventional coal plant used for comparison. This plant was scaled from the TAG East/West Central coal plants with limestone scrubbers (200–500 MW) to yield a plant facilities investment of $1207/kW (January 1984 dollars) and a heat rate of 9850 Btu/kWh.

A production costing analysis of the substitution options was performed. The unphased IGCC plant tended to be operated at a higher capacity factor than the new conventional coal

**Table 1**
**PRESENT VALUE OF UTILITY SYSTEM REVENUE REQUIREMENTS**
(December 1985 $ million)

| | Conventional Coal Expansion | Unphased IGCC Expansion | Phased IGCC Expansion |
|---|---|---|---|
| Production costs | | | |
| Coal cost | 1659 | 1655 | 1653 |
| Oil cost | 30 | 24 | 47 |
| O&M cost* | 415 | 383 | 370 |
| Subtotal | 2104 | 2062 | 2070 |
| Fixed charge† | 422 | 455 | 377 |
| Total | 2526 | 2517 | 2447 |

*This includes variable O&M costs for all units and fixed O&M costs for the new capacity only.

†This is only the fixed charge for the capacity that is unique to each scenario.

plant. This dispatching difference was due to differences in the incremental operating costs associated with the unphased IGCC plant, the existing coal plants on the utility system, and the new coal-fired plant with limestone scrubbers. The IGCC plant's incremental operating costs were lower than those of the existing coal plants, which in turn were lower than those of the new coal-fired plant. As a consequence, the IGCC plant was dispatched before the existing coal plants, whereas the new coal plant with scrubbers was dispatched after the existing coal units.

Despite this dispatching difference, the results of the unphased IGCC scenario and the new conventional coal scenario were identical (within the accuracy of this analysis) in terms of the total present worth of revenue requirements. These results are summarized in Table 1, where the savings in fuel costs and operating and maintenance costs of the unphased IGCC plant are shown to be counterbalanced by its higher fixed charge relative to the conventional coal plant.

In the unphased IGCC scenario, the 362 MW of capacity were installed in the year 1993 in place of 362 MW of new conventional coal capacity. By contrast, the phased IGCC capacity was installed in three increments in 1993, 1994, and 1995. The production costing analysis for this case revealed an anticipated increase in total oil consumption by the utility system because the first two phases consisted of oil-fired capacity. On balance, however, the fixed-charge savings associated with matching load growth through phased capacity addition more than offset the higher fuel costs in the early years. In terms of the present worth of revenue requirements, the phased IGCC scenario yielded a very substantial saving (about $70 million) over the unphased scenario.

Although the results of this kind of economic analysis are expected to vary somewhat from utility to utility, the preliminary results indicate that phased IGCC capacity addition may indeed have broad applications. *Project Manager: Allison Lewis*

## SCALE CONTROL IN GEOTHERMAL SYSTEMS

*Native geothermal fluids, whether steam or hot brines, are chemically complex and unstable substances. Resources throughout the western United States range between two extremes—the vapor-dominated resources of northern California's Geysers field, with noncondensable gas content as high as 5 wt% and dissolved solids content as low as the parts-per-million level, and the hypersaline liquid resources of southern California's Imperial Valley, with dissolved solids content approaching 30 wt%. Controlling the behavior of these fluids is critical to successful geothermal power production, and scale formation from these fluids is the major cause of availability loss in geothermal power generating facilities. The objectives of EPRI research in scale control are to understand the behavior of geothermal fluids and to learn how to predict and control that behavior.*

The three primary components of scale in geothermal systems are carbonates, silica and silicates, and sulfides and sulfates. Carbonate scale is formed when brine pressure is reduced, allowing gaseous carbon dioxide to escape from solution and resulting in increased brine pH and production of carbonate ions:

$$2HCO_3^- \rightarrow CO_2 \uparrow + CO_3^{--} + H_2O$$

Calcium ions and the newly formed carbonate rapidly combine and precipitate as calcium carbonate scale:

$$CO_3^{--} + Ca^{++} \rightarrow CaCO_3 \downarrow$$

This is a major problem in production wells where large pressure decreases occur.

Silica scale is formed as the brine temperature falls and the silica reaches supersaturation; most geothermal brines come out of the ground saturated in silica. Because silica precipitates far more slowly than does calcium carbonate, silica scales are distributed throughout geothermal power systems. Although carbonate scales are acid-soluble and may be removed by chemical treatment, silica scales may be extremely hard and are most commonly removed by physical means.

The pH increase brought about by the release of carbon dioxide at lower pressure also produces sulfide ions, which can combine with metal ions commonly present (such as lead) to form sulfide scale:

$$S^{--} + Pb^{++} \rightarrow PbS \downarrow$$

Sulfide scale is distributed throughout geothermal power plants.

Sulfate ions, present in equilibrium with sulfide, are readily formed when geothermal fluids are exposed to the atmosphere. In direct-contact condensers, for example, they also combine readily with available metal ions (such as barium) and form scale:

$$SO_4^{--} + Ba^{++} \rightarrow BaSO_4 \downarrow$$

Sulfate scale is most common in the final stages of geothermal power plants, where the fluid temperatures have decreased significantly from reservoir temperatures.

Scale control has always been a problem in geothermal power generation because of the large quantities of scale formed. Uncontrolled calcium carbonate and silica scales may choke production of some reinjection wells in less than a month, slowing fluid flow; scales that form on turbine buckets, blades, and seals may lead to measurably decreased turbine efficiency and power output in just a few days.

More recently, another aspect of scale formation has become of interest. Some of the heavy metals that readily form scale with sulfide, sulfate, and other ions are environmentally sensitive species. Although the formation of environmentally sensitive scale on the order of grams or kilograms per year does not approach the formation of silica or calcium carbonate scale (on the order of tons per year at a 5-MW plant), controlling these scales is part of efficient and cost-effective power production from geothermal resources.

In the mid 1970s EPRI recognized the complexity of scale control in geothermal systems and developed a strategy to address the problem. Individual projects are working toward understanding, prediction, and control of scale formation, and proposed scale-control technologies are being evaluated for performance and characterized for applicability.

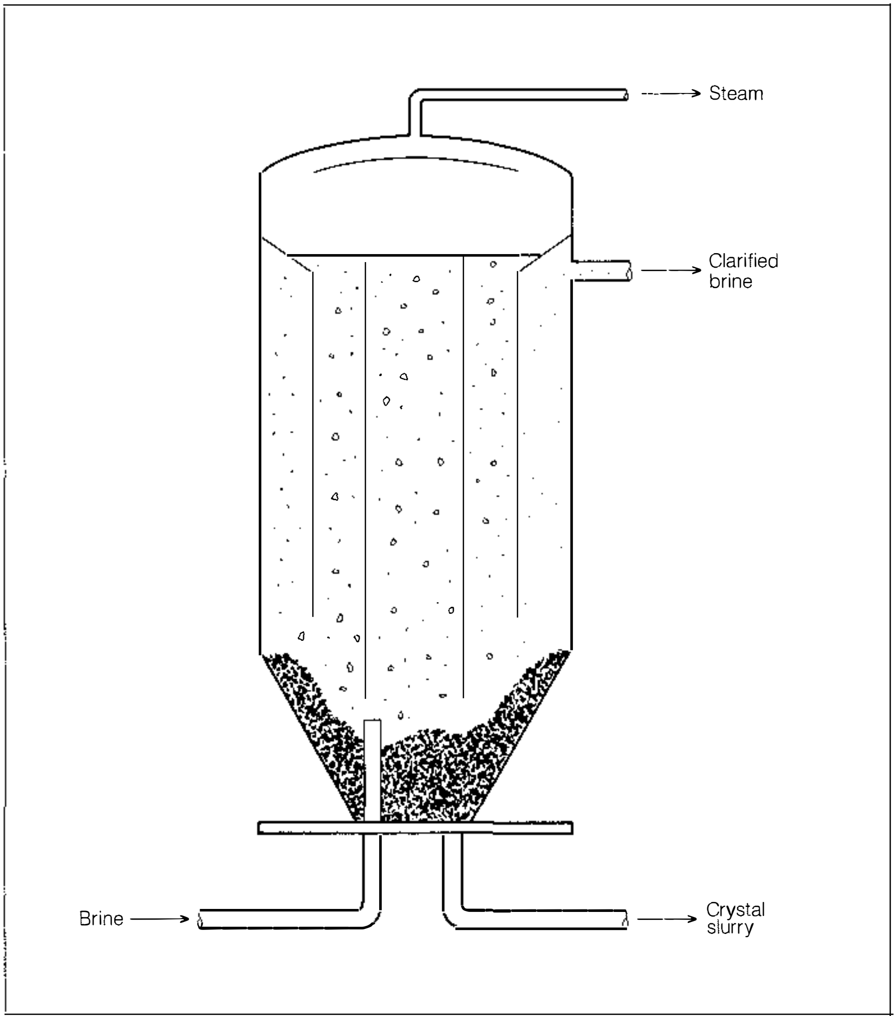
### Mineral precipitation

Selective mineral precipitation in flashed-brine power plants is the concept that led to the design and fabrication of a crystallizer unit by The Ben Holt Co. (RP1525-3). With this device, EPRI will investigate the feasibility of bulk scale removal by selective crystallization upstream of a power plant boundary.

During the production of steam by flashing, brine reaches supersaturation when mineral concentrations are increased by the loss of liquid water to steam and when the temperature decreases. In flashed-brine facilities, severe scaling is common in and just downstream of the flash vessels, with the flash temperature and pressure and the brine characteristics determining the precipitates formed. In general, carbonate and sulfide precipitate during a high pressure–high temperature flash, and silica precipitates during a low pressure–low temperature flash.

The EPRI flash-crystallizer vessel (Figure 2) was designed with maximum flexibility to encourage mineral precipitation under controlled conditions. Brine containing scale-forming species enters the vessel and is flashed. Steam exits the top of the vessel, and stabilized brine, now a slurry, exits the bottom. The overall process combines steam production by brine flashing with mineral precipitation. The vessel will be tested in 1985–1986 on several brine types to evaluate the effects of temperature, pressure, scale type, supersaturation, particle contact, and recirculation rate. Optimal conditions for selective precipitation and improved design features of flash-crystallizer vessels for specific brine conditions will be determined during the field test.

Figure 2 This flash-crystallizer vessel was designed and built for the investigation of controlled mineral precipitation and removal at flashed-brine plants. In the vessel steam is produced and solids are removed from geothermal brine under controlled conditions.




### Continuous mechanical scale removal

Declining heat exchanger performance in geothermal systems is largely caused by scaling on surfaces of the heat exchanger. For binary plants, where geothermal brine circulates on the tube side of the heat exchangers, potentially large quantities of hard silica scale pose a problem in scale removal that is not encountered in conventional steam plants.

An EPRI study of continuous mechanical scale removal by Heat Exchanger Systems, Inc., and Foster-Miller, Inc., has provided a summary of the mechanical scale-removal technologies currently available, both on-line and off-line; an evaluation of geothermal experience; and a recommendation for further development toward geothermal application (RP1525-5).

On-line mechanical methods for removing scale from heat exchanger tubes include sponge ball systems, brush-and-cage systems, abrasive cleaning, and ultrasonic cleaning. No geothermal experience has been reported for any of these methods.

In the sponge ball system, sponge rubber balls are continuously recirculated so that each tube is wiped at least once every five minutes. This technique minimizes shutdowns for manual cleaning and reduces the need for adding biocides, but it is a complex, highly mechanized system requiring frequent ball inspection and replacement and frequent component adjustment, and it may lead to tube abrasion. For geothermal application, new ball materials would be required to withstand brine temperatures and pressures, and the recirculation system would have to be modified to prevent scale buildup.

The brush-and-cage system, in which brushes are pushed through heat exchanger tubes and returned by flow reversal, also minimizes shutdowns for manual cleaning, reduces the need for biocides, and ensures the cleaning of each tube; but this technique requires reverse-flow piping and valves, is limited to straight tubes, and may result in substantial tube abrasion. For geothermal applications, new brush and tube materials would be required to withstand the brine temperatures and pressures.

Injection of abrasive material is the least costly on-line cleaning method, but it results in uneven cleaning and may cause excessive tube erosion. Technology would have to be developed to remove abrasive materials from geothermal brine before it is reinjected into the ground.

Scale removal by ultrasonic vibration shows no promise for geothermal application because current technology cannot accommodate the length of geothermal heat exchanger tubes (up to 60 ft, or 18 m).

Off-line tube-cleaning methods examined in this study include air- or water-driven brushes; power-driven scrapers, cutters, and vibrators; and water lances. No geothermal experience is documented for these methods. The techniques share the advantage of requiring no special maintenance surveillance, such as is required by on-line methods, but share the disadvantages of requiring equipment downtime and of resulting in continuously changing heat exchanger performance (i.e., improvement after cleaning, then continuous degradation). Of the off-line methods, water lances show the most promise for geothermal application.

EPRI is currently evaluating whether to proceed with developing and testing mechanical cleaning systems for geothermal heat exchangers.

**Table 2**
**ESTIMATED ARSENIC DISTRIBUTION FOR HYPOTHETICAL 5-MW POWER PLANT**
(lb/yr arsenic)

| Location | $H_2S$ Concentration 12 ppm | 147 ppm | 720 ppm |
|---|---|---|---|
| Well bore | $1.4 \times 10^6$ | $3.2 \times 10^4$ | $2.9 \times 10^3$ |
| Turbine | 490 | 11.5 | 1.1 |
| Cooling-tower sludge | 36.5 | 0.85 | 0.08 |
| Cooling-tower drift | $4.3 \times 10^{-3}$ | $1.0 \times 10^{-4}$ | $9.4 \times 10^{-6}$ |

Note: These values represent the theoretical worst-case deposition rate; they were calculated by using estimated thermodynamic constants: $\Delta H° = 24{,}200$ cal and $\Delta S°_{25} = 30.2$ cal deg$^{-1}$.

### Trace elements in geothermal systems

Concern about the formation of environmentally sensitive scales led EPRI to begin to examine the distribution of trace elements in geothermal systems. Arsenic was chosen as the first element to be studied because of its presence in some native geothermal fluids at parts-per-million levels.

A theory on arsenic distribution was developed for EPRI by James W. Cobble, using the thermodynamic model (RP1525-6). Factors controlling arsenic concentration in geothermal fluids include hydrogen sulfide, hydrogen, the minerals orpiment ($As_2S_3$) and realgar ($As_2S_2$), and temperature. Gaseous arsenic trichloride is unlikely to be present in geothermal fluids except under extreme conditions (pH <2, $Cl^-$ >100,000 ppm).

Work to date resulted in a theory that gaseous arsenous acid is the volatile arsenic species in geothermal fluids. It is theorized that this species is responsible for the distribution of trace quantities of arsenic in power plants. Using estimated thermodynamic constants for the postulated arsenous acid gas, arsenic deposition in a hypothetical 5-MW single-flashed-brine plant was calculated at various levels of hydrogen sulfide (Table 2). Measurements at operating plants indicate that the trends in arsenic deposition predicted by this theory are correct; the values given in Table 2 represent the maximum theoretical deposition rate (thermodynamic rate) for the hypothetical plant.

Experimental studies are under way, and field data are being collected to corroborate the theory. If it is demonstrated to be successful, the theory will be used to investigate the feasibility of reducing the amount of arsenic in geothermal power systems. Similar studies are being planned to examine other environmentally sensitive trace species, including boron, cadmium, and mercury. *Project Manager: Mary E. McLearn*

# R&D Status Report
# COAL COMBUSTION SYSTEMS DIVISION

Kurt Yeager, Vice President

## STEAM TURBINE BLADE PERFORMANCE

*Blade failures are the leading cause of steam turbine unavailability for large fossil fuel plants in the United States, costing utilities more than $235 million annually. They are also a major cause of the general decline in availability experienced by large units during recent decades. More recently, changes in operating mode have further increased the problems of many large units. When nuclear capacity and more-efficient fossil fuel units began to supply baseload demand, many fossil fuel baseload plants were relegated to cycling or peaking duty. Because these displaced units were designed for steady operation at full load, unsteady operations have caused recurrent problems with components, including steam turbine blading. This report describes EPRI's R&D efforts to address the problems of blade failure and blade erosion.*

### Low-pressure turbine blading

Three-fourths of all steam turbine blade failures occur in low-pressure turbines, and about 75% of these—half of all blade failures—occur in the last two rows of blades.

The predominant causes of low-pressure blade failure are three parameters that can act either individually or in combination: operating environment, susceptible material, and stress (especially fatigue stress). A recent EPRI survey of 494 units indicated that unless the root cause of a failure is identified and corrected, it is likely that the problem will recur in the same group of blades (RP1856-1). The survey also revealed that the proportion of repeat failures is increasing over time. EPRI R&D on low-pressure blading concentrates on three areas: identifying the major contributors to blade failure, developing alternative technologies to improve blade reliability and extend operating life, and demonstrating developments in host utility plants.

*Operating environment* One approach is to alleviate the effects of corrosive contaminants in the feedwater cycle. Although corrosive substances, such as chlorides, occur in steam at only a few parts per billion, concentrations increase dramatically when the dry steam begins to condense in a turbine. The so-called Wilson line condensation usually occurs at the last or next-to-last row of blades. Contaminants in the steam become concentrated in the condensate 10,000 times or more, forming very corrosive solutions. This accounts, in part, for the disproportionate share of blade failures in these locations.

Under RP1408-1 Southern California Edison Co. (SCE) showed that steam purity is primarily determined by the performance of the condensate polishers. The most severe corrosion of low-pressure turbine blades occurred in once-through units when condensate polishers had been operated beyond ammonium breakthrough, allowing high levels of chlorides to be released into the steam. High levels of sulfate, too, were sometimes released from freshly regenerated polishers. High chloride concentrations in the steam caused significant corrosion of the turbines, and high sulfate levels caused pitting and tube failures in the reheaters. Changing from a high-chloride to a low-chloride caustic for anion resin regeneration, together with other changes in regeneration procedures, produced more than a 10-fold reduction in chloride leakage and significant reductions in sulfate leakage. The relatively low level of corrosion that SCE found in its drum-type units resulted from the effectiveness of steam separators in the boiler drums.

EPRI research efforts are continuing to improve sampling and monitoring of chemical contaminants in the feedwater cycle, as well as to develop methods for preventing contaminants or removing them from the feedwater. Operating guidelines are planned for monitoring and controlling water chemistry in fossil fuel plants to minimize localized corrosion effects in steam turbine blades and boilers. An interim draft report of the water chemistry guidelines will be available for industry review in mid 1986.

*Susceptible material* To improve blading materials for low-pressure turbines, EPRI has focused on the titanium alloy Ti-6Al-4V, which has superior resistance to corrosion fatigue in chloride environments and better resistance to stress-corrosion cracking than do stronger materials. Following initial laboratory development and qualification by Westinghouse Electric Corp. (RP1264), a row of freestanding titanium alloy blades was installed in December 1984 in a low-pressure turbine of Martin Lake Unit 3, operated by Texas Utilities Generating Co. (Tugco). For comparison, a parallel row of 17-4PH stainless steel blades with the same configuration was installed at the opposite end of the same turbine, giving rows of two different blade materials essentially the same operating environment.

Strain gages attached to the rotating blades monitored the magnitude and frequencies of the stresses in both rows of blading. Miniature transmitters mounted in the balance holes of the rotor sent the data to stationary receivers and on to a trailer equipped with instruments for on-line and recorded spectrum analysis. Load, steam pressure, and temperature were varied over a wide range of design and operating conditions to accurately determine how titanium alloy would hold up in a real-life application.

The test results were encouraging in that the ratio of actual-to-allowable fatigue stress for the titanium alloy blades was only one-half the ratio observed in the 17-4PH steel blades. Titanium's inherent corrosion resistance and light weight make it an ideal blade material where corrosion-assisted fatigue in blading airfoils or root sections has occurred or where stress-corrosion cracking of disk rim attachment areas is a concern. Westinghouse and Tugco will observe both rows of blades for several years to determine the titanium alloy's long-term performance.

Protective coatings are another means of improving blade resistance to corrosion. SCE and Westinghouse cooperated to develop and test several corrosion-resistant coatings for low-pressure blades (RP1408-3). After screening 24 candidate nonproprietary coatings, SCE subjected the most promising materials to an exhaustive field test program at its Redondo Unit 7. Duplex nickel-cadmium and ion-vapor-deposited aluminum were found to be best in these field demonstrations. Currently, SCE has 23 groups of coated blades operating on several units of its power system.

*Stress* To provide utilities with an independent means for analyzing and troubleshooting vibration-related blade failures, Stress Technology, Inc., is developing an interactive computer code, BLADE (blade life algorithm for dynamic evaluation) under RP1856-2. The code uses finite-element techniques to analyze the causes of blade failure and to evaluate alternative blade configurations (Figure 1). To evaluate the probability of fatigue failure in a turbine blade under specific operating conditions requires calculation of both steady and dynamic stresses at critical locations, and comparison with the material's fatigue strength under those conditions.

The dynamic model for an entire blade group is built up by mathematically replicating a single-blade model. The group model is used to calculate vibration characteristics, including (1) natural frequencies and mode shapes, and (2) forced responses to the applied excitation spectrum and blade damping. The excitation spectrum is either applied as program input or developed from turbine stage dimensions and operating characteristics.

The BLADE code employs the local-strain approach to fatigue analysis, predicting the time for crack initiation to occur in high-stress regions, such as the blade root fillet. The method takes account of alternating stresses of various amplitudes and accumulates their damage to predict the time of failure.

Although the BLADE code is still under development, Public Service Electric & Gas Co. has already applied it in troubleshooting a failure in the control stage at its Hudson station. Further utility experience with the code will be obtained through a full-scale demonstration and validation test scheduled to be conducted on a next-to-last (L – 1) blade row at SCE's Huntington Beach station.

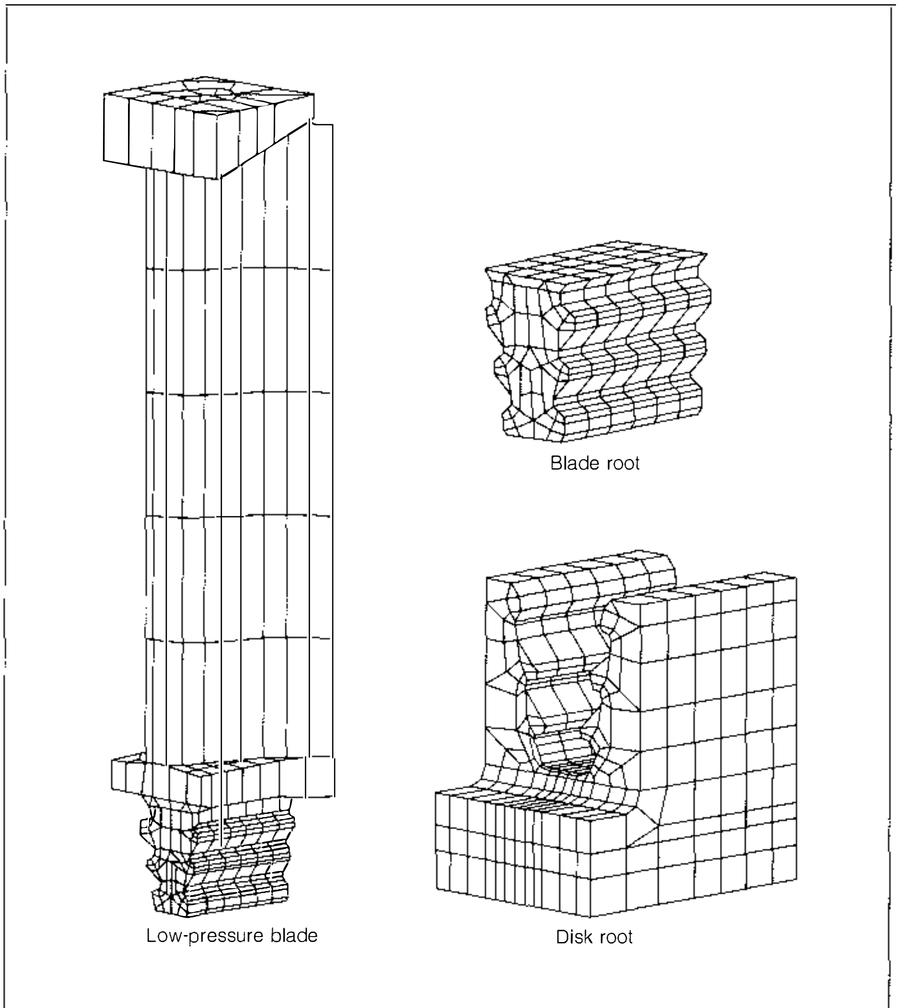



Figure 1 Steam turbine blade and disk model from BLADE, an interactive computer code that uses three-dimensional finite-element analysis to determine the fundamental cause of blading failures, assess alternative operating and design strategies, and recommend corrective action.

**Solid-particle erosion**

Solid-particle erosion (SPE) of steam turbine buckets or blades, nozzles, and control valves has been a problem of concern to U.S. utilities for many years. It is generally agreed that erosion damage is caused by oxide scale that detaches (exfoliates) from boiler tubes or steam leads and becomes entrained in the steam flow to the turbine, eroding components of the steam path and turbine. The resulting alteration of blade and nozzle profiles, increased surface roughness, and increased spill-strip clearances cause a significant reduction in turbine efficiency, as well as increased maintenance and repair costs.

Exfoliation of boiler scale is generally perceived as a steady-state phenomenon, but the maximum rate seems to occur on startup or during transients in operating conditions. First-stage components in high-pressure and intermediate-pressure turbines usually suffer the most severe damage, but valves and other system components are also affected.

Turbine damage caused by exfoliated particles from the superheater and reheater tubing and piping steam surfaces can increase fuel and maintenance costs by more than $3 million a year in a typical 600-MW plant.

Through the SPE research effort, EPRI is developing retrofit solutions for existing plants as well as improved designs and materials for new installations. The three approaches that are being pursued are as follows.

- Curtailing the source of particulates by means of improved alloys and tube-surface treatments to reduce exfoliation (RP644) and by operating procedures (such as sliding pressure operation or full-arc admission) to avoid abrupt temperature changes and minimize particle/steam velocities (RP1885)

- Removing particulates from the steam before they reach vulnerable components (nozzles, valves, blading)—for example, by using turbine bypass systems to shunt the particles directly into the condenser (RP1879)

- Using hard-faced coatings to increase the erosion resistance of turbine blades, nozzles, and valves (RP1885)

Under RP644-1, Foster Wheeler Development Corp. has developed an aqueous chromate solution treatment that reduces scale formation and exfoliation and can be applied in the field to existing boiler components. A field-applied chromate treatment of the superheater section and steam piping of a drum boiler was completed at Long Island Lighting Co.'s Glenwood Landing station in spring 1982. Tube samples removed at two annual outages since then have shown no significant signs of scale formation or exfoliation.

This field demonstration indicates that the chromate process can successfully treat a full-scale utility boiler. Exposure of the treated surfaces to steam produces a modified scale that contains an iron-chromium spinel layer. By reducing the mobility of the $Fe^{++}$ ions and the inward diffusion of oxygen, the spinel layer reduces the rate of scale growth by a factor of 3, thereby minimizing the need for frequent chemical cleaning of superheaters, reheaters, and main steam lines. Foster Wheeler will evaluate the long-term benefits of the chromate treatment over a five-year period at the Glenwood Landing station. EPRI plans a follow-on demonstration of the chromate process in a once-through boiler.

Practical and cost-effective solutions to the SPE problem are hampered without information on particulate characteristics and concentration during turbine operation. Such information is needed before developing particulate removal devices, establishing less-erosive operational modes, and evaluating protective coatings for susceptible components. The steam-turbine-related efforts aimed at reducing or eliminating the effects of SPE are divided into four parts under RP1885, which is being carried out by General Electric Co.

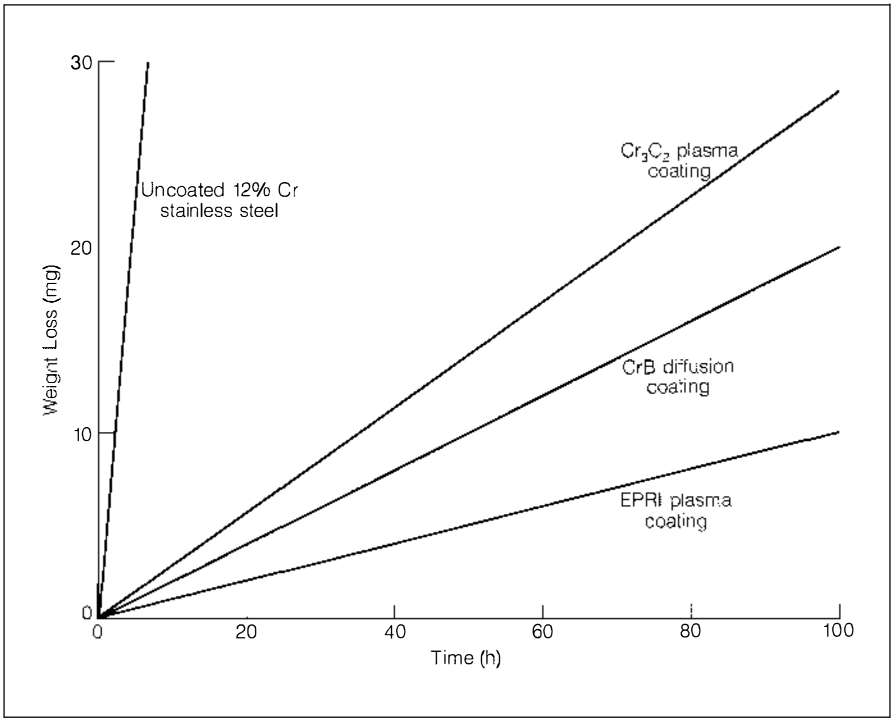
- An isokinetic monitoring system that samples main steam at two separate locations to characterize the size, hardness, and density of the solid particles and to evaluate the erosivity of the steam-particle mixture on coated test specimens.

- An evaluation of both plasma-sprayed cermet-type coatings and diffusion-bonded coatings. The three best coatings have been applied to specimens in the field test chamber developed as part of the isokinetic monitoring system. Results from the laboratory tests are shown in Figure 2.

- A field test program to demonstrate and integrate the results of the particle characterization and coatings evaluations. The isokinetic steam sample and monitor, the erosion test chamber, and the data acquisition system have been installed and are operating at the Stuart station of Dayton Power and Light Co. The candidate coatings and solid-particle characterization will be evaluated by varying operating conditions through a matrix of representative inlet pressures, temperatures, and startup rates, including full-load operation. The data from these tests will be used to determine the size and density distribution of solid particles in the steam and will be correlated with concurrent data from the erosivity tests conducted on the coating samples.

- An economic evaluation methodology that can be used by a utility for cost-benefit analysis to find the optimal solutions to minimize or eliminate SPE. The methodology models various combinations of remedial actions and maintenance and repair activities, assessing the effects of erosion damage on unit heat rate and forced outage rate and computing the annual cash flows for economic evaluation by using the following analysis methods: annual revenue requirements, levelized annual revenue requirements, short-term analysis, and breakeven analysis. The methodology has been implemented in the SPEEDM computer code with an interactive format for easy use with little training. The output of the program compares the SPE prevention alternatives under consideration and can be readily used by utility management in the decision-making process.

Figure 2 In solid-particle-erosion laboratory tests of several representative candidate coatings, airfoils were subjected to air with 25-ppm chromite particles at 1040 ft/s (317 m/s) and 1000°F (540°C). The three coatings shown here performed best and were selected for further testing. A newly developed EPRI plasma coating (patent pending) suffered the least erosion weight loss.




After the field evaluation tests have been completed, field demonstration tests with actual turbine blades and nozzles will begin in a number of utility plants. The data from the SPE characterization tests will be used in conjunction with an SPE analytic modeling code to help develop and test improved SPE-resistant blade profiles, operation and maintenance guidelines, and particle-steam separation equipment. Investigators will monitor these retrofit applications for several years to assess the long-term performance of the improved components and systems. *Project Manager: Thomas McCloskey*

# R&D Status Report
# ELECTRICAL SYSTEMS DIVISION

John J. Dougherty, Vice President

## TRANSMISSION SUBSTATIONS

### Advanced power transformer

Increased fuel costs and inflation over the past 10–15 years have emphasized the conservation of both energy and capital. Although by itself a transformer is a very efficient piece of equipment, electric power flows through several transformers on its way from the generators to the consumer. Hence, a small energy loss in one transformer is multiplied by three or four, making the total loss much more significant. For this reason, a primary goal of EPRI's R&D is to develop more-efficient power transformers. The development of amorphous core steel is designed to address core (no-load) losses (RP1290, RP2236). A new project with Westinghouse Electric Corp., with Phelps-Dodge Cable & Wire Co. as a subcontractor, addresses load losses (RP2618).

Load losses are primarily dissipated in the windings. One can view the losses as related to conductor resistance. Hence, using larger conductors would seem to reduce the losses. However, with alternating currents, magnetic field effects tend to push the currents toward conductor surfaces (skin effect), thus reducing the effective conductor area used for current conduction. Hence, just increasing the conductor area is not an economical approach. Further, the magnetic fringing fields of the windings induce eddy currents into the conductors. Because these currents are more significant in thick conductors, transformer manufacturers use multipart conductors; they also employ transposed cables for the windings because dividing the conductor into many small branches reduces the conductor skin effect as well as the eddy-current losses.

About five years ago Phelps-Dodge invented a new conductor, known as a transposed ribbon cable because it is a flat cable made up of many transposed parts. The cable promises to reduce losses and permit the construction of compact windings. Hence, the winding may help reduce the load losses by reducing the skin effect as well as the eddy-current losses; but it may also permit the building of smaller coils, thus reducing the winding resistance as well. Smaller transformers will allow manufacturers to ship larger-capacity transformers if needed, but this is a fringe benefit and not a goal in itself. This project should demonstrate the feasibility of producing windings that satisfy transformer manufacturers' requirements, as well as of building windings with the new conductors. This phase of the project has been completed. *Program Manager: Stig Nilsson*

### Amorphous-metal-core power transformers

The magnetic and electrical properties of a family of iron alloys developed by Allied Corp. hold the promise of reducing no-load losses in transformer cores to one-third the value achieved by the best conventional steels. These materials are unique in that they are solidified from liquid so rapidly that an orderly crystalline atomic structure cannot form. Instead the alloy has an amorphous arrangement of atoms, like glass. The thinness, high resistivity, and noncrystalline nature of the material result in low eddy-current and hysteresis losses.

The objective of a series of projects with Allied and Westinghouse Electric Corp. (RP1290-1,-2,-3, and -4 and RP2236-1 and -2), which began in 1978, is to verify that reduced losses can be obtained at a reasonable cost.

Earlier work at Allied concentrated on identifying the preferred alloy or alloys and then developing a continuous casting operation with the necessary automatic features to stringently control dimensions of the amorphous metal ribbon. Parallel work at Westinghouse studied the suitability of the material for transformer applications and investigated methods that could be used to build a power transformer core from the new material.

A 500-kVA three-phase transformer with an amorphous core has been built for a five-year field trial. The unit is about to be installed on the Niagara Mohawk Power Corp. system for field operation.

Researchers are now working on producing cold-welded laminate approximately 0.25-mm thick from multiple layers of thin ribbon. Allied has purchased, refurbished, and installed a used rolling mill for producing this laminated material, which they call Powercore. Powercore has slightly higher losses than the individual thin ribbon, and there is a cost associated with the consolidation process; however, its increased thickness and better space factor are advantages to transformer manufacturers. Work is proceeding to determine ways of maximizing the throughput of the rolling mill while retaining strict dimensional control.

Alternative core construction techniques using moderate-scaled corelets are being studied. Key issues are space factor, labor costs, and electrical losses. Westinghouse has also developed appropriate methods for cutting the amorphous ribbon. A preliminary plan is to use automatic equipment to cut and stack the material for power transformer cores. Installation of such a pilot line will be our next major goal. *Project Manager: B. L. Damsky*

### HVDC circuit breaker

The November 1984 *EPRI Journal* (p. 54) described the development of two HVDC circuit breakers under RP1507. One of these was an air-blast type, developed by Brown Boveri Corp. It was successfully tested up to 2200 A at 400 kV. The application of this breaker requires a dc system control and protection strategy that deliberately delays the tripping of the circuit breaker until the converter control reduces the fault current to the breaker interrupting rating.

At the conclusion of this development, EPRI initiated a new project to enhance the breaker capability in two ways (RP1507-4).

□ By increasing the maximum current interrupting rating to 4000 A at a system voltage of 500 kV dc

□ By reducing the overall fault clearing time by allowing breaker tripping immediately after detection of a fault

This work started in March 1985 and is scheduled to be completed in August 1986. The expected result will be a commercially available 500-kV, 4000-A HVDC circuit breaker with a fault-clearing time of approximately 30 ms. *Project Manager: Joseph Porter*

## DISTRIBUTION

### Method to predict VRD cable neutral corrosion

During the early 1960s utilities installed millions of feet of direct-buried copper concentric neutral cables for their distribution systems. On the basis of past experience with copper grounding systems, utilities did not expect the copper neutrals to corrode. However, as early as the late 1960s reports of neutral corrosion started to appear. To address this problem, EPRI conducted several research projects to determine the mechanisms causing corrosion and the corrective action utilities should take. Although these projects were successful, none led to a reliable method of detecting neutral corrosion in the ground without excavating the cables.

A new project with Harco Corp. was intended to address this need by developing a method that utilities could use to determine the probability that copper concentric neutrals are corroding or that conditions are favorable for corrosion to occur (RP2200). The researchers developed a method, using data available within the industry, to predict corrosion and determine which factors influence its occurrence.

The study has had beneficial results. Corrosion appears related to two factors: surface potential and soil resistivity. Neither of these factors alone is a reliable indicator, but used together they reveal a pattern. In general, corrosion is less likely to occur as the potential becomes more negative and soil resistivity becomes higher. The final report will include a method that can be used to predict corrosion on the basis of potential and resistivity, but the limited amount of data makes its reliability questionable.

Although this method has limited value in helping utilities to predict corrosion, it could be used to compare two or more areas of potential corrosion and enable a utility to concentrate its efforts accordingly. More details of the study and the statistical methods used will be presented in the final report, which is expected to be available in mid 1986. *Project Manager: Harry Ng*

## POWER SYSTEM PLANNING AND OPERATIONS

### Transient and midterm stability

Power systems have grown larger and interconnections between utilities have grown more complex in recent years. Therefore, the need has increased for power system planners and operators to analyze power system transients after the sudden loss of lines or generators. Experience indicates that the effects of such disturbances on large systems are widely felt for as long as several minutes. However, traditional analysis programs have been designed to be accurate for about 10 s or less.

The goal of this research project is to develop a program that would extend the period of analysis by adding models of equipment that come into play during disturbances up to 5 min long (RP1208). A second objective is to reduce the required computer time to acceptable levels (computer time of 1 h/s of model time is not unusual). The new program is based on the transient/midterm program developed under RP745 and other work done in RP670 and RP763. New features include an improved, two-terminal dc transmission line model, as well as improved machine and auxiliary models. An enhanced output analysis package has also been developed.

Host utility testing began in December 1984 and was completed in July 1985 at six utilities: Consumers Power Co., Ontario Hydro, Pacific Gas and Electric Co., Philadelphia Electric Co., Public Service Co. of Indiana, Inc., and Western Area Power Administration. Boeing Computer Services Co. and Ontario Hydro are providing support to the IBM and VAX versions of the program, respectively. Additional work on improving the program speed and fixing minor problems discovered during host utility testing is now under way. The program will be available for distribution through the Electric Power Software Center by March 1986. *Project Manager: John Lamont*

### EMTP improvement

A four-year effort (RP2149) to improve the electromagnetic transients program (EMTP) has been begun by EPRI in cooperation with the following eight organizations, which make up the Development Coordination Group (DCG): the Bonneville Power Administration, the Canadian Electrical Association, Hydro-Québec, Ontario Hydro, the U.S. Bureau of Reclamation, the Western Area Power Administration, ASEA, and the Central Research Institute of the Electric Power Industry of Japan. Developed by the Bonneville Power Administration and others, EMTP has been widely used over the last 15 years to study high-speed electrical system transients. Bonneville has distributed EMTP to more than 150 organizations worldwide.

Beginning next year, new versions of EMTP that incorporate the changes developed by EPRI and DCG will be available only through EPRI. The first version, to be released early in 1986, will be followed by three annual revisions, each significantly more powerful than the preceding program.

The combined effort is expected to total more than 70 person-years by 1989 and will improve EMTP models, program features, and documentation. The largest effort is planned in developing transformer models. Also, work is under way to produce better circuit breaker models, transmission line models (including corona, lightning arresters, HVDC, and static VAR control), rotating-machine models, and cable models.

Program features are also being improved, including replacement of cumbersome and confusing input and output formats, extension of present program initialization capabilities, and elimination of many troublesome program quirks. Auxiliary programs that automatically produce network equivalents for EMTP studies and calculate fatigue in turbine generator shafts (using the EPRI FATIGUE program) have been included in the first program release.

In the critically needed area of EMTP documentation, a variety of items are completed or under way. A new user's manual (rule book) is available with the program. An EMTP primer was published in September 1985 (EL-4202). A workbook for new users, developed as a part of seminars held in October 1985, will soon be available and may be used in future EPRI-sponsored seminars. A series of application guides is now being developed, as is documentation of the EMTP code itself. An EMTP theory book will be available in late 1986.

EPRI has undertaken responsibility for maintaining EMTP until the demand for this service no longer justifies its expense. A users group and hotline service is now being initiated and will be continued until the users are self-supporting. *Project Manager: James V. Mitsche*

## OVERHEAD TRANSMISSION

### TLMRF: Milestone in full-scale testing

EPRI's Transmission Line Mechanical Research Facility (TLMRF) has been testing full-scale electric transmission structures for over two years. The tests have been both (1) cosponsored ones between a utility and/or fabricator and EPRI and (2) research fully funded by EPRI.

The objective of the utility and/or fabricator in a majority of the cosponsored tests to date has been to demonstrate the ability of the structure to withstand a specific set of loads; this kind of test is called a proof test. Accomplishing this objective does not usually require instrumentation because proof tests only verify the load-bearing ability of a tower. They do not analyze or test a design for its member stresses.

In contrast, EPRI initiated a project (RP2016) to determine stress levels in individual steel members and to compare those values with values obtained by computer analysis. With the aid of EPRI-developed computer software, the rapidly growing data base is leading to two key developments: accurate assessment of bending moments in structural elements and prediction of stress distribution patterns throughout lattice steel towers.

As a result of this project, researchers have recently predicted the element most likely to fail for all but 23% of towers tested; those that failed in unexpected locations did so at an average of 95.4% of the total load planned for the tower.

A recent breakthrough occurred when test data warned of the impending failure of a particular element, and the test was arrested in time to prevent damage to the overall structure. Researchers were thereby able to avoid the cost of repair and further testing. In effect, the real capacity of the structure was defined without destructive testing and associated repair.

The significance of this breakthrough is that for the first time, engineers confidently anticipated individual component failure and the mode of failure during the test. Although tension and compression strain gage readings could be taken easily, the calculated bending moment on a critical element determined the time and location of failure. Now with the aid of computer analysis assessment of load distribution throughout the tower is possible. The data system automatically searches for the structural components under greatest stress; it then predicts member collapse on the basis of data collected to that point in the test.

TLMRF personnel are assembling a large and useful data base that will enable researchers to further define load distribution in a tower; but to be more effective, the data acquisition and control systems need additional instrumentation, which is being installed. As the staff gains more experience on a larger range of designs, the TLMRF facility will be able to offer a wide variety of services, such as determining the behavior of particular detailed designs, nondestructive development testing, and testing to help upgrade structures.

For example, as a result of the test that was arrested before failure, the participating utility, Tennessee Valley Authority, was able to reduce the weight per tower in a planned 100-mi (160-km), 500-kV line and save approximately $100,000. Eliminating several members and a number of bolts per tower from the original design will also reduce the cost of erecting the system. In addition, this test supplied data to improve the calculations of force distributions by analytic methods and provided the needed confidence for better designs and modifications in the future.

Experienced tower designers are aware that good tower details are essential for a reliable structure. Tower members that have been designed adequately will not perform satisfactorily if they are not properly detailed. The goal of a tower designer must be to detail end connections so that eccentricities through joints in the tower are kept to a minimum. (Many failures have resulted from bending stresses induced by eccentric connections in transmission line towers.) One objective of EPRI's research is to monitor stresses around a selected joint in a tower where some degree of eccentricity occurs. This information will form the basis not only for evaluating axial forces in members around this selected joint but also for evaluating induced bending stresses.

Another technical benefit of research at TLMRF is engineers' ability to evaluate the amount of support a tension member in a tension compression cross brace will provide to the companion member in compression. In many instances, weight reductions would be possible if the unbraced length of the compression member on the *X*-*X* axis could be taken as 0.5 times the total length. Opinions vary throughout the industry on this subject. The TLMRF facilities monitor the forces in the individual members. The collected data should be helpful in resolving this question.

Clearly, TLMRF is paying substantial dividends in terms of useful results and will continue to do so; with the current investment in expanded testing, it will be even more competitive with traditional proof testing. *Project Manager: Paul Lyons*

**A case study: Building a transmission line along a railroad**

Before the publication of a final report in 1983 (EL-3301, Vols. 1 and 2), engineers planning to build transmission lines along railroads had very little technical information on which to base their designs. Traditional methods for mitigating electromagnetic induction often called for installation of an expensive, heavily shielded signal cable buried along the track to replace the pole-mounted signal wires. No reliable calculation methods were available to predict induction effects before a power line was energized, and no real effort had been made to look for improved, lower-cost mitigation methods.

Researchers hoped that the report supplied the needed information, but the real proof of the value of this research would be to use its results. About the time the project was completed, Arizona Public Service Co. approached EPRI with an ideal situation for applying the research results. APS was engineering a 525-kV line that would be parallel to a railroad for about 65 mi (105 km) of its length. The railroad's consultant had recommended the usual mitigation—installation of a magnetically shielded cable—at an estimated cost of several million dollars. The challenge for all parties, APS, EPRI, and the railroad, was to assess the power line's effect on the railroad facilities, review the mitigation options, and select one that would be acceptable to the railroad yet reduce the cost of the original plan, all before actually building the line. The objective of a follow-on project (RP1902-2) was to apply the results of RP1902-1 on APS's 525-kV line. The funding was shared by APS and EPRI, and the project objective of acceptable mitigation at a reduced cost was achieved. The results are detailed in EL-4147.

Instead of the expensive shielded cable, APS and the railroad decided to use a new technology—an electronic track circuit signal system. This system was far less costly than the shielded cable system, and it eliminated the need for the overhead signal wires because this system uses the rails for conductors. The power company enjoyed the lower cost; the railroad appreciated eliminating the high-maintenance-cost pole line.

The report also describes other technical issues, in particular the effect of phase-to-ground faults on the railroad system. During transmission line faults, the large unbalanced current in the faulted phase is magnetically coupled to the rails, causing substantial voltage to appear across the rail-insulating joints. Protectors installed to shunt lightning strokes from the rail to ground will fire, thus preventing damage to the insulating joint. But if the current is above the protector rating, the protector may be destroyed. If lightning were to strike the rail or if the power line were to have another fault, the protection would be gone, and the full voltage would appear across the insulating joint, causing it to puncture. The solution was to install protectors of sufficient rating to withstand the fault conditions. The computer program CORRIDOR can be used for this design.

In addition to the technical achievements demonstrated in this case study, the project proved to be an outstanding example of how the two companies, working with EPRI, could jointly solve technical problems and reach a solution beneficial to both. The final report details how researchers used CORRIDOR to analyze this case, how they investigated the various mitigation options, and the rationale for selecting the mitigation used. The report is recommended for any power company planning to build a transmission line along a railroad. *Project Manager: John Dunlap*

## UNDERGROUND TRANSMISSION

### Watersaw* concrete cutting equipment

Under contract to EPRI, Fluidyne Corp. has developed an efficient water-jet concrete-cutting unit for use by the utility industry (RP7860-3). Using pressurized water mixed with a garnet abrasive, the Watersaw can cut asphalt or concrete economically and with exceptional edge quality.

The major advantage this cutting system has over conventional machinery is its operating economy. On-the-job expendables are diesel fuel, water, and abrasive. High-quality, low-cost cuts have been demonstrated in the field at three locations (Table 1). The cost per foot of cutting shown is the cost of the abrasive expended, calculated by using the commercial bagged price of 10¢/lb, which is higher than the bulk price.

**Table 1**
**FIELD-TEST RESULTS FOR WATERSAW HANDCART ASSEMBLY**

| Characteristic | Location A | Location B | Location C |
|---|---|---|---|
| Cut length | 63 ft | 20 ft | 40 ft |
| Linear traverse rate | 5 ft/min | 4 in/min | 1.5–2 ft/min |
| Water use rate | 4 gal/min | 6 gal/min | 4 gal/min |
| Abrasive use rate | 1.5 lb/min | 1.5 lb/min | 1.5 lb/min |
| Horsepower | 50–60 | 50 | 50 |
| Substrate material | Asphalt and concrete | Concrete (hardened) | Asphalt/macadam |
| Thickness | 4–6 in | 6–7 in | 4–6 in |
| Cost/ft | 3¢ | 45¢ | 10¢ |

Watersaw is a versatile multifunction cutting package. Three cutting devices can be used with the same power package: a hand-held gun, a lawn tractor cutting unit, and a self-propelled precision-cutting handcart. The power package currently being used is diesel powered, with a trailer-mounted direct-drive triplex piston pump. Under design consideration is a new, near-commercial prototype trailer based on utility and construction crew input. This advanced trailer will use a hydraulically driven intensifier developed for EPRI. The contractor is also developing lower horsepower devices for manufacturing functions and architectural jobs.

Watersaw was displayed at the International Construction and Utility Equipment Exposition in Kansas City, October 1–3, 1985. *Project Manager: Thomas J. Rodenbaugh*

*Watersaw is an EPRI trademark.

# R&D Status Report
# ENERGY ANALYSIS AND ENVIRONMENT DIVISION

René Malès, Vice President

## EPIDEMIOLOGY AND RISK ASSESSMENT

*Attention to the role of environmental toxics in human health is increasing. One way to investigate this role is through epidemiology, the study of disease in human populations. By examination of the pattern and distribution of disease, epidemiology can often identify the factors associated with the disease. Epidemiology can also help assess the risk associated with particular levels of exposure to those factors. EPRI was instrumental in bringing experts together in a symposium to discuss the best ways to develop and apply epidemiologic evidence.*

Epidemiologic data are often the first indication of the presence of a health hazard, either in an industrial setting or in the larger community. When an adverse health situation is noted, careful investigation is necessary to identify possible causative agents in the environment. The health effect and the role of the suspected cause must then be further studied under controlled conditions in the laboratory by either in vitro tests or tests on animal surrogates. Although such toxicologic tests may help identify the causative agent, they can only imply (not confirm) a human health effect; epidemiology alone is the powerful tool that provides the prime evidence for judging the relation between an environmental insult and the associated disease in an exposed population.

In helping to estimate the size of the risk associated with a particular level of exposure, epidemiology can also provide perspective. For example, epidemiologic evidence suggests that 30% of cancer deaths are caused by cigarette smoking, whereas only 4–5% of cancer deaths result from exposure to occupational hazards.

For many epidemiologic questions, however, it is often difficult to analyze population data and extract an unambiguous indication of cause and effect because the information is obtained from observation rather than from controlled experiments. In other words, factors other than exposure to some chemical may be the cause of a disease.

These issues were addressed at a symposium that dealt with epidemiology and its use in risk assessment (RP2310-3). The symposium, held May 14–16, 1985, in Columbia, Maryland, brought together epidemiologists and scientists from a range of disciplines with risk analysts and management representatives from government and industry. Leon Gordis, professor and chairman of the Department of Epidemiology at Johns Hopkins University School of Hygiene and Public Health, chaired the symposium. Over 375 attendees registered.

EPRI's cosponsors in the symposium were the following organizations in industry and government: American Industrial Health Council, American Petroleum Institute, Centers for Disease Control (Center for Environmental Health), Chemical Manufacturers Association, U.S. Department of Energy, U.S. Environmental Protection Agency, Gas Research Institute, Johns Hopkins University School of Hygiene and Public Health, National Center for Health Statistics, and National Institute of Occupational Safety and Health.

The symposium had the following objectives.

- To encourage the collection of appropriate data and the use of epidemiologic data in human health risk assessment
- To identify specific uses and advantages of epidemiologic methods and approaches for health risk assessment
- To provide informed guidance to scientific managers who must interpret epidemiologic findings and develop policy
- To encourage cooperation and communication between epidemiologists and decision makers so that the needs of risk assessment are treated consistently in the development and planning of epidemiologic studies

The focus was methodologic issues in epidemiologic studies. One key issue discussed was the evaluation and interpretation of epidemiologic evidence and the application of epidemiologic findings to public health issues that arise in the regulatory process and in major industrial decisions. "Epidemiologic evidence" was defined and distinguished from "any human data." For example, a single data point or small numbers of data inappropriately collected should not be used as the basis for risk assessment. The symposium explored some of the methodologic issues that can arise in epidemiologic investigations (both in data collection and in data analysis), such as the problem of reconciling disparate results, and explored their effect on the evaluation of risk.

The approach to gathering exposure information for epidemiology studies was also deemed important by the symposium. In retrospective studies, where data are collected for exposures that occurred before the initiation of the studies, more resources are needed for the development of more-rigorous estimates of exposure. In particular, epidemiologists should work closely with industrial hygienists in defining both the source and the extent of exposure. Estimates of individual exposure may be modified by activity patterns. Individuals may spend different amounts of time in the exposure area. (For example, in studies of indoor pollution a housewife may be exposed for longer periods than any other member of the family.) In general, the symposium speakers concurred that exposure studies are investigations of a dynamic time process and that both measures of exposure and analytic techniques must reflect these dynamics. The discussion emphasized that because risk assessment is also a predictive process, information must be collected and analytic techniques developed to accommodate this aspect of risk assessment.

Generally, the symposium speakers concurred that although the demonstration of an effect in a defined population represents the ultimate evidence for identifying a causative relationship between human health and an environmental factor, additional methodologies must be developed to evaluate the accuracy and strength of an observed association and to answer the following questions.

- Can a causative agent be specifically identified when other possible agents are present?
- Does the lack of a readily identifiable association mean that none exists?
- Is the number of cases observed sufficient to provide significant data?
- Is the degree of association sufficient to support a causal rather than a chance association?
- How can studies yielding contradictory information be reconciled?

Some techniques for handling these questions already exist, and others must be developed to provide a more rational basis for setting standards.

Publications from this symposium will provide methodologic assistance for evaluating epidemiologic evidence in developing public policy. In addition, workshops will be held in the future to discuss new methods for improving current assessment tools.

Publication of the symposium proceedings as a monograph is planned by Oxford University Press. This publication should become an important reference volume for epidemiologists and decision makers at all levels in government, industry, and the academic community. It is EPRI's hope that this symposium also initiated an awareness of the need to develop further the epidemiologic tools for establishing rational public policy decisions. *Project Manager: Abraham Silvers*

# R&D Status Report
# ENERGY MANAGEMENT AND UTILIZATION DIVISION

Fritz Kalhammer, Vice President

## CAVITATION REPAIR AND PREVENTION

*Cavitation occurs in varying degrees throughout the wide spectrum of hydroelectric turbine types, sizes, and ages. It can result in high maintenance/repair costs, revenue losses from excessive downtime, operating inefficiency, and reduction of useful equipment life. Because prevention and repair of cavitation damage are major availability issues, utilities have attempted (with varying degrees of success) to mitigate the problem. EPRI sponsored a study of these industry efforts in order to collect and assess utility experiences and to provide recommendations and guidelines for minimizing cavitation effects in existing and planned installations. The study covered the following topics: inspection, repair, modifications, design, model tests, guarantees, materials, quality control, and R&D.*

The study team was led by Acres American, Inc. (now Acres International Corp.), of Buffalo, New York (RP1745-10). Acres selected the St. Anthony Falls Hydraulic Laboratory, which has done cavitation research for industry and the U.S. Navy, to do the computer data reduction and analysis work, and selected Allis Chalmers Corp. and Dominion Engineering Works to provide manufacturing and model testing information.

The essence of this type of research is to accumulate a substantial and well-defined data base. To obtain such a data base, Acres devised a detailed questionnaire. The questionnaire was sent to 270 owners/operators of reaction turbines installed since 1950 and having a capacity of 20 MW or greater with a discharge diameter in excess of 3.05 m (120 in). Because of the nature of their design, impulse turbines (i.e., Pelton wheels) are not generally subject to cavitation pitting and, therefore, were not included in the study. The project team received more than 220 responses from operators representing 40,000 MW, or approximately 50% of the total U.S. hydropower capacity.

Investigators visited a number of plants to discuss cavitation repairs and repair problems with plant personnel. In addition to the information obtained through the questionnaire and these visits, the data base incorporates data from a similar study undertaken recently by the Canadian Electrical Association. Other industry reports also contributed vital information, including one published in 1953 by the Hydraulic Power Committee of the Edison Electric Institute (Publication No. 52-14). To help analyze the data base from both a practical engineering and a basic scientific perspective, input was obtained from turbine designers and manufacturers as well as from academic investigators engaged in fundamental cavitation research.

### Cavitation damage

Although cavitation is a complex phenomenon, it can be described simply as the formation of vapor bubbles in a liquid caused by a reduction in fluid pressure. In most cases, the pressure drop that initiates the cavitation results from an increase in local fluid velocity. As expressed in the Bernoulli theorem, an increase in velocity manifests itself as a corresponding decrease in static pressure. When the static pressure drops below the vapor pressure at any point, cavitation bubbles may form. However, because the fluid's surface tension or tensile strength resists bubble formation, bubbles must be initiated by nuclei of vapor and noncondensable gases in the fluid itself, in the fissures of solid particles, and in cracks or crevices at the boundaries of the flow.

The actual damage is caused by the collapse of the bubbles as they move into regions of higher pressure. Their collapse, which occurs in microseconds, produces intense shock waves (or explosions) that emanate from the collapsed center and create impulse loads on the runner material. The shock waves create small craters, which crack and spall the surface. This metal loss, called cavitation pitting or cavitation damage, can reduce component weight measurably as time passes. The appearance of a metallic surface eroded by cavitation can range from lightly frosted to very rough with deep pits.

Cavitation influences the operation of hydraulic machinery in two basic ways. It causes noise (shock waves) and vibration in the equipment, and it can pit or erode the water passage surfaces, which is usually detrimental to the machine's hydraulic performance. Sufficient engineering information and test data can improve hydroturbine equipment design so that vibration and lost performance resulting from cavitation are not problems.

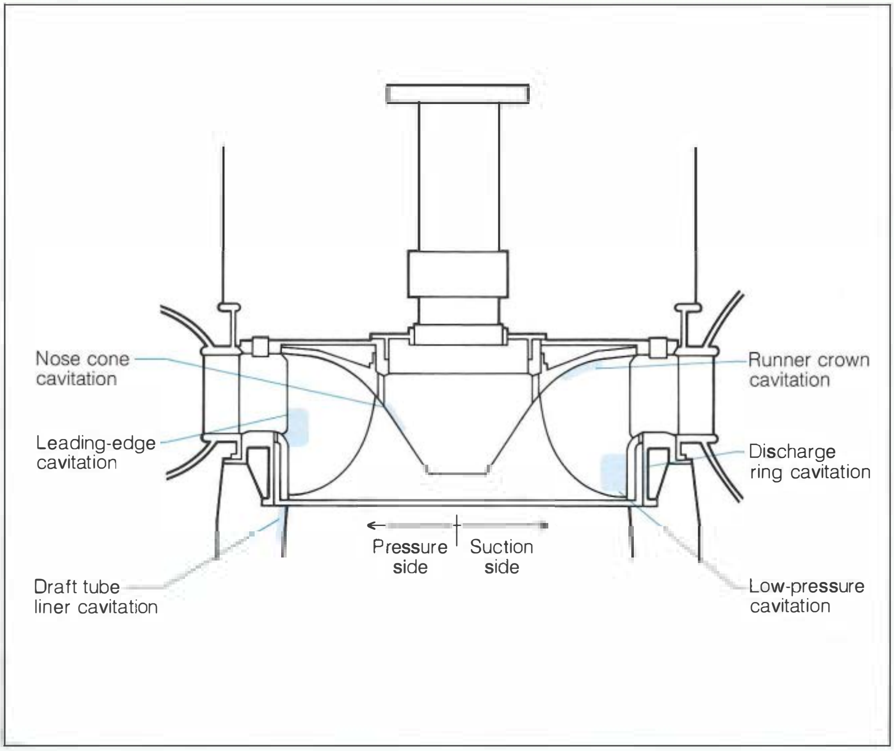
### Inspection and repair of existing units

The descriptions of cavitation erosion obtained from the questionnaires and from direct contact with plant operators highlighted and improved understanding and knowledge of the locations and severity of cavitation damage on hydro machinery components. Figure 1 shows the principal areas of a Francis turbine that are susceptible to cavitation damage. The final report for this project will provide guidelines for diagnosis and remedial action for each of the various locations of cavitation damage.

To reduce the pitting on successive repairs, plant owners are now making repairs with much more care than they have in the past. They are giving the final runner blade profile more attention, stressing the quality of the weld, and using more-erosion-resistant repair materials. The consensus of plant owners is that an effectively planned and executed repair program can minimize further cavitation pitting.

Inspection and evaluation of cavitation pitting of the turbine runner and the components within the water passage is usually done every one to four years; the most common inspection is annual. Inspections are performed from a maintenance platform installed below the runner; some are performed on special blade-contour ladders. An inspection typically compares new damage with that observed on previous inspections (Figure 2). The influence of cavitation repairs on unit downtime depends

Figure 1 Typical areas of cavitation pitting in a Francis turbine. An EPRI project is developing diagnostic and repair guidelines for each of the susceptible areas.



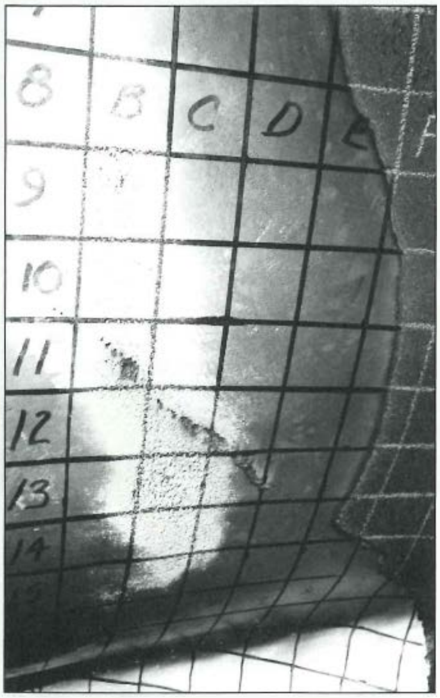



Figure 2 Evaluation grids like this one are used on turbine runner blades in order to compare cavitation pitting from inspection to inspection. Here the cavitation damage appears as the rough, lighter area near the center of the shiny stainless steel overlay.

on the extent of the damage, as well as on the requirements for other maintenance work in the plant. Most repair work is made during the annual maintenance period. If repairs are made during an outage specifically for that purpose, elimination of pitting would obviously decrease the unit downtime by the duration of the outage. Many operators commented that downtime could probably be reduced about 25% if there were no repairs for cavitation damage.

During the study investigators made the following observations and developed the following conclusions.

▫ Although inspections are usually done annually, minimizing cavitation damage can increase time between inspections to about four years for turbines and two years for pump-turbines. The study provides a sample analysis of how to economically schedule maintenance for cavitation damage.

▫ Standard methods of recording pitting damage would be advantageous for monitoring progress throughout the plant's life and for discussions with turbine suppliers, other utilities, and outside repair crews.

▫ Most repairs have been made with stainless steel weld; other, more-cavitation-resistant materials show promise. The use of stainless steel plate is limited to areas not affected by vibration.

▫ Plant owners use a variety of repair procedures; standard procedures for preparing, welding, finishing, and modifying would enhance repairs.

▫ Runners are modified under certain circumstances, but guidelines are necessary to determine when and how such modifications should be accomplished.

▫ Unfused materials have been frequently used; however, success is limited primarily because bonding the unfused material to the runner is difficult.

## Guarantees and mitigation in new units

Guarantees against cavitation in technical specifications for turbines and pump-turbines are contractual agreements that state the amount of pitting damage a plant owner will tolerate during the guarantee period. Such guarantees can only be established between a plant owner and a manufacturer during planning and negotiations because a guarantee depends not only on machine design, material, surface conditions, and unit setting but also on operating conditions and duration.

Plant histories show that guarantees before 1970 had no discernible effect on control of cavitation pitting damage. As repair and maintenance costs and the value of replacement energy have increased, so too has the importance of guarantees. In general, cavitation guarantees have altered from such general statements as "there shall be no excessive pitting," as specified in the early 1950s, to more demanding conditions based on metal loss, operating modes, materials, quality control, and other considerations.

Inasmuch as extremely tight guarantees could add to equipment costs, allowing slightly more metal loss and specifying finer profile and surface finish tolerances, plus greater use of cavitation-resistant materials, may be more prudent and cost-effective. In effect, use of guarantees and mitigation measures to reduce damage on new equipment requires a balance between ideal and practical considerations.

Although cavitation guarantees are common in the hydro industry, there is still some question about their value. When the average guaranteed allowable weight loss per year for units installed after 1970 (as determined by regression analysis) is compared with the actual weight loss for those units having cavitation guarantees, the result is excessive data scatter with little correlation; in fact, 40% of those units have suffered cavitation erosion exceeding the average amount guaranteed. Thus, the methods used by the industry in establishing guarantees are less than adequate.

Guidelines for improved consistency in the specification of guarantees are as follows.

- Specify acceptable methods for measuring weight loss during the guarantee period
- Specify the guarantee period (e.g., 8000 hours of operation)
- Indicate acceptable maximum depth and minimum area of damage
- State and define operating restrictions (i.e., above maximum power, below minimum power, and below minimum tailwater level) and express them in terms of operating hours during the guarantee period, the duration of which should depend on the intended operation of the plant
- State mandatory periodic inspections by the equipment supplier's hydraulic engineer during the guarantee period (e.g., 2000, 4000, and 8000 hours)
- Specify requirements and conditions for modifications and repairs to be done by the equipment supplier as part of the contract
- Use IEC Publication 609 and Amendment No. 1 to 193 as reference documents
- Specify, more clearly, material selection and quality control during manufacturing

The cost of achieving zero or minimal cavitation on new equipment can be evaluated by using the following factors: unit setting, material selection, quality control, replacement power costs, permissible cost of repairs, loss of turbine component life, number of units, and operating requirements. Although some of these factors require subjective judgment, all affect the cost of the project, and the first three can usually be determined accurately by the bidding process.

### Model tests

A turbine model test program normally includes tests to determine the machine's cavitation characteristics, to help refine the design so that it meets cavitation performance, and to confirm the selection of the unit setting with respect to tailwater level. The tests consist of operating the turbine or pump model at constant head, wicket gate opening, and runner blade angle and observing the influence of varying the tailwater elevation. Alternatively, the tailwater may be held constant while operating the model through a large range in head.

Visual observations of cavitation on the model are being used more widely to identify leading-edge cavitation that results from high- and low-head operations, low-head cavitation, leakage cavitation on propeller and Kaplan turbines, and the onset of low-pressure cavitation on the suction side of runner blades. Good correlation between visual observation on the model and pitting locations on prototypes has been reported by turbine manufacturers. The use of fiber optics on pump-turbines has been advanced for the complex blading configurations.

Several manufacturers are also experimenting with acoustic techniques. They have noted correlation between acoustic emission of piezometric transducers and both high- and low-load cavitation. Such tests show promise, particularly for Francis and pump-turbines; the constant source of background cavitation noise over most of the operating range makes measurements more difficult in Kaplan turbines.

From a review of cavitation model test information and data, project personnel made the following observations.

- Cavitation model tests are performed on most turbine and pump-turbine designs and are an important part of the selection of the setting and the operating restrictions for hydroturbine equipment.
- Cavitation break curves provide insufficient test information, and visual observations should supplement these data.
- Inspectors should sketch their observations, as well as take photographs; video tape can also be used for future reference.
- Guidelines for minimum test head for cavitation model tests should be established.
- Computer modeling in conjunction with physical models provides a powerful tool for cavitation analysis, although further development of computer modeling is necessary.
- Although still in the research stage, acoustic measurements show promise for both analyzing model test results and correlating models to prototypes.

Cavitation is a complex problem considerably influenced by site-specific conditions. No magic prevention or remedy exists. Nevertheless, experience shows that cavitation can be controlled effectively by appropriate testing and procurement practices and by preventive repair and maintenance practices. *Project Manager: James Birk*

## REVIEW OF RESIDENTIAL ENERGY-EFFICIENT TECHNOLOGIES

*For the past several years EPRI has been conducting surveys of utility demand-side management activities. These surveys, designed to identify and describe utility end-use programs, show considerable activity in a wide range of programs dealing with efficient-energy-use technologies in the residential sector. To consolidate survey information and disseminate the results of utility experience with these technologies, EPRI initiated a project to review more closely the cost and performance of nine specific residential water-heating and space-conditioning technologies (RP1940-10). The study, which was recently completed, compiles data from 26 utilities and presents both qualitative and quantitative information on the technologies evaluated in their programs.*

More information on energy-efficient technologies is particularly important to the utility industry because of the growing interest in demand-side programs designed to meet a range of objectives, from reducing overall load through conservation to reducing peak load, maintaining existing market share, and selectively building off-peak load. Although many utilities have gained considerable experience with a few technologies, solid information on the actual field performance of energy-efficient technologies remains scarce.

The objective of this review was to gather empirical data on technology cost, installation and operation, energy use, and effect on load shape. The review was also to provide information on utility promotional and monitoring techniques, as well as to identify gaps in knowledge about technology performance. A key aspect of the study is the analysis and presentation of findings in consistent terms and formats.

The study included all technologies deemed mature, readily available to utilities and customers, and the subject of at least one utility test from which data on field performance and practical experience could be obtained. Investigators surveyed utility programs on water heater retrofit measures, heat pump water heaters, heat recovery water heaters, air-source heat pumps, add-on heat pumps, ground-source heat pumps, high-efficiency air conditioners, and building envelope retrofit measures. They also surveyed standards for improving the thermal integrity of newly constructed buildings.

### Water heating

Of the several retrofit measures available for reducing water heating energy consumption, this study surveyed insulating blankets, thermostat setback, and insulating bottom boards. Installed costs ranged from $10 to $55, depending on the type of measure. Compared with conventional water heaters, insulating blankets saved an average of 260–710 kWh annually; setting back thermostats saved 390–600 kWh; and insulating bottom boards saved 50–160 kWh. A combination of all three measures was estimated to save 560 kWh/yr, on the basis of a standard set of operating conditions. Such a saving corresponds to a demand reduction of 76 W in winter and 51 W in summer per installation.

The survey team reviewed both integral and add-on heat pump water heaters (HPWHs). An integral HPWH is a single unit containing both the heat pump components and a water heater tank. An add-on unit is a heat pump designed to be added to an existing water heater tank. Performance was reported in terms of annual performance factor (APF), a ratio of the annual energy requirement of a conventional water heater to that of an HPWH to meet a fixed water heating load. APFs for both types of heat pumps ranged from 1.49 to 1.80, with an average of 1.64. This average implies that an HPWH will consume about 40% less, compared with a conventional electric water heater.

The study showed no significant differences in the reported performances of integral and add-on units, nor did any correlations exist between performance variations and regional or climatic characteristics. All five utilities surveyed reported that HPWHs exhibited lower peak demands and higher load factors than did electric resistance water heaters. It is estimated that HPWHs reduced average peak load by about 30% and 40% for a winter day and a summer day, respectively (Figure 3).

Two types of heat recovery water heaters (HRWHs) were reviewed: those installed on central air conditioners and those installed on heat pumps. For units installed on air conditioners, APFs ranged from 1.21 to 1.35 and averaged 1.28. Performance of units installed on heat pumps was higher, with APFs ranging from 1.17 to 1.61 and averaging 1.39. These results imply that heat recovery from air conditioners saves 22% annually and from heat pump units, 28%, compared with electric resistance water heaters. Climate and cooling loads were the major factors influencing performance. Summertime coincident peak load reductions ranged from 0 to 0.5 kW per installation. The single utility reporting winter load impacts cited a coincident demand reduction of 0.6 kW per installation.

### Space heating and cooling

The review compared air-source, add-on, groundwater, and ground-coupled heat pumps used for space heating with conventional residential electric furnaces. Excluding ductwork, installed costs for air-source heat pumps ranged from about $880 to $1600/ton of capacity, with higher-performance units commanding a higher price. Two of the three reporting utilities provided performance data, with seasonal performance factors (SPFs) ranging from 1.60 to 2.04. (SPF is the ratio of seasonal heating output to total energy input.) Two utilities reported coincident demand reductions of 1.97 and 3.85 kW per installation, influenced primarily by prevailing outdoor temperature at the time of the utility's winter peak. Average heating load and relative heat pump size also affected the demand.

An add-on heat pump is an air-source unit used in conjunction with a forced-air fossil fuel furnace. Four utilities reported installed costs ranging from about $900 to $1140/ton of capacity, with average cost for a 3-ton system at about $3150. Many of the surveyed utilities were interested in the load growth potential of these types of unit, and reported findings showed that the heat pump provided 46–82% of a customer's normal heating load. (The percentage varied as a function of heat pump size.) SPFs ranged from 1.68 to 2.00, and increases in sales ranged from 4400 to 12,000 kWh/yr per installation. Customers who installed these units saved 27–33% in operating costs. These savings were influenced largely by prevailing energy costs and the efficiency of the fossil fuel system used for comparison.

Three utilities reported on programs with groundwater and ground-coupled heat pumps. A groundwater heat pump (GWHP) is an open-loop system that uses water from a well or pond as its heat source. A ground-coupled heat pump (GCHP) is a closed-loop system that continually recirculates a heat source fluid through a below-ground heat exchange loop. Both system types use essentially the same heat pump hardware, which ranged in installed costs from $2300 to $4000. Costs for the water-source and ground-coupled heat exchange subsystems differed, however, resulting in average reported installed costs of about $4000 for a 3-ton GWHP

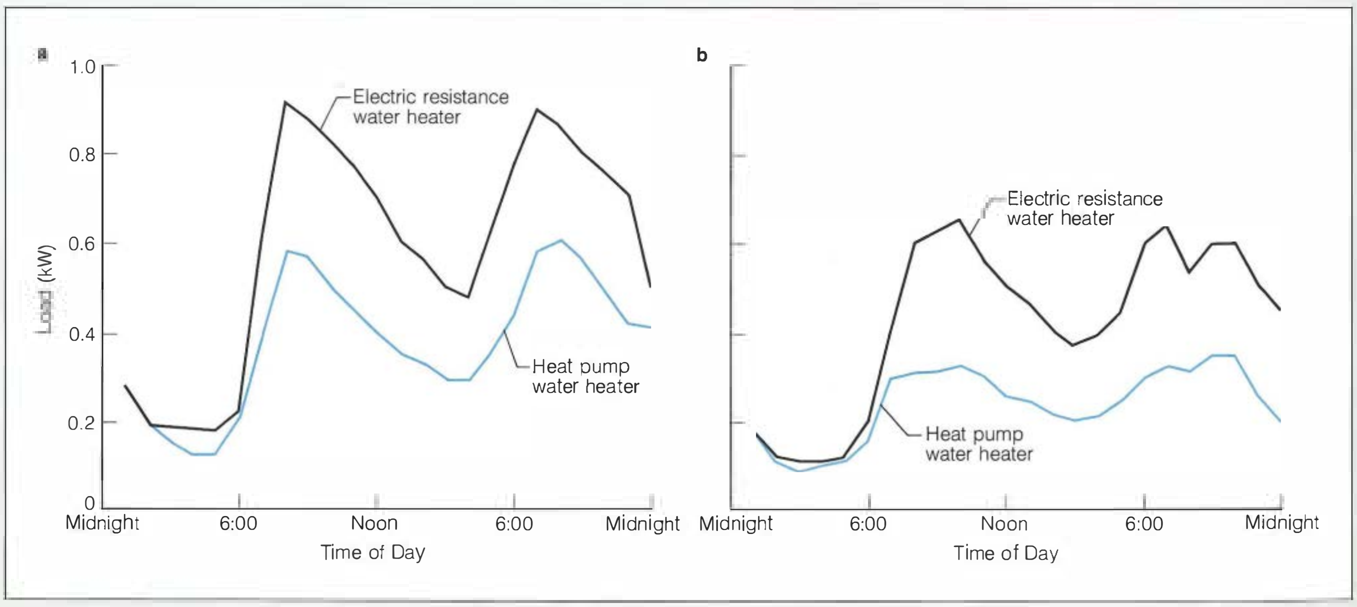
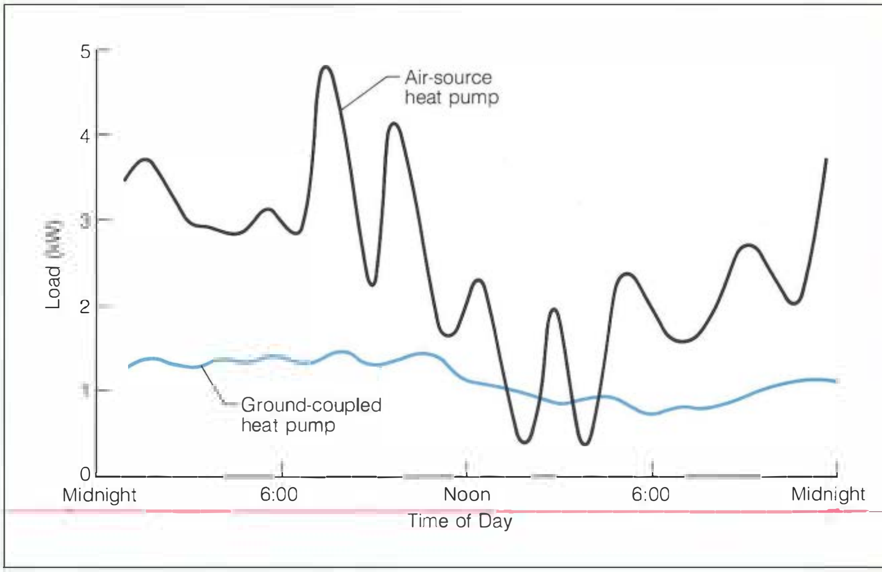



Figure 3 On the basis of heat pump water heater data from five utilities, this technology's load characteristics were compared with those of a conventional electric resistance water heater for (**a**) a typical winter day and (**b**) a typical summer day.

and $5000 for a 3-ton GCHP. Reported average SPFs were 3.0 and 2.73 for groundwater and ground-coupled units, respectively. Performance factors are high, compared with those of air-source heat pumps, because the heat sources remain fairly constant, relatively unaffected by outdoor temperatures (Figure 4). One utility reported peak demand of 4.6 kW for ground-coupled heat pumps, compared with 29 kW for an all-electric system.

High-efficiency central air conditioning was the only space-cooling technology reviewed in the survey; a single utility provided the data. Estimated costs averaged $1500 for an installed 2-ton air conditioner with a 9.0 seasonal energy efficiency ratio (SEER), the ratio of cooling delivered (Btu) to energy input (Wh) over the entire cooling season. Costs were affected by unit size and rated efficiencies. Performance results indicated an 18% average reduction in energy use when air conditioners with rated SEERs of 9.0 replaced units with rated SEERs of 6.5. The more efficient systems reduced peak demand an estimated 0.23–0.36 kW/ton.

Figure 4 Utility field data were used to compare space-heating load for an air-source heat pump and a ground-coupled heat pump on a very cold day. Because it is less affected by outside temperature, the ground-coupled technology showed better performance.




### Building thermal integrity

Four utilities tested numerous retrofit measures for improving the thermal integrity of residential buildings, thereby reducing space-conditioning loads. These measures included caulking and weather stripping, attic insulation, crawl space insulation, storm windows, and storm doors. The utilities often reported retrofits in combination and sometimes included water heater retrofit measures in their reports.

Costs varied with the type and extent of installed measures (e.g., the R-value of insulation), the installer (customer or contractor), and the accessibility of the spaces to be treated. Attic insulation costs ranged from 40–85¢/ft$^2$, or 2.1–3.7¢/ft$^2$ per unit R-value of insulation added. Per house costs for all other building retrofit measures were supplied by a single reporting utility and included $74 for caulking, $1462 for crawl space insulation, and $3062 for storm windows and doors.

Retrofit measures saved 2210–6630 kWh annually per installation, an average of 10–29%. The measures were estimated to reduce winter demand 0.1 to 0.6 kW per house; reductions were higher for single-family than for multifamily units.

### Reliability

The utilities surveyed were asked to describe the reliability of the technologies under review. Water heater and building retrofit measures were perceived to be highly reliable by the respondents, as were high-efficiency central air conditioners and add-on and air-source heat pumps for space heating.

Heat pump water heaters were rated as less reliable. Four of the five utilities surveyed cited a variety of mechanical and installation problems, including heat exchanger blockage and failure of compressors, pumps, or controls. Quality of installation appeared to affect long-term reliability significantly. The single utility that reported heat pump water heaters as more reliable was testing newer units than were the other utilities. This finding implies that more recently manufactured equipment may perform better.

Reports on the reliability of heat recovery water heaters varied widely from utility to utility. Three of the five reporting utilities cited serious problems; the other two reported satisfactory findings.

Field experience with ground-source heat pumps was insufficient for accurate reliability assessment.

### Discussion

The empirical data collected during this study were standardized to the extent possible for consistency in terms of units of measurement and other factors. The resulting information facilitates a comparison of utility experiences. The study should be valuable to utilities considering the promotion of one of these technologies or concerned about the effect of a technology's penetration in the marketplace. Study findings will be entered into a computerized data base, along with the findings of a related review of residential load management technology (EPRI EM-3861). Readers should note, however, that many of these field test results are based on small samples and tests of limited duration. The most common test methodology was control group or flip-flop testing, where both efficient and standard versions of a technology are installed at the same site and operated during alternating time periods. Billing data are also being used as a resource for measuring energy impacts, although most of the tests reviewed in this study acquired data from site monitoring and instrumentation.

In three specific cases a dearth of documented test data indicates a need for further investigation.

- Reliable information on the effect of high-efficiency air conditioners on demand and energy is sparse, even though a number of utilities have initiated aggressive promotional programs for this technology.
- Current-model heat pump water heaters appear to perform better and more reliably than the older units reported on in this study, suggesting the need for additional tests.
- Information on ground-source heat pumps is sparse, even though the technology appears to hold promise for reducing both demand and energy use.

*Project Managers: Steven Braithwait and Veronika A. Rabl*

# R&D Status Report
# NUCLEAR POWER DIVISION

John J. Taylor, Vice President

## SIGNAL VALIDATION TECHNOLOGY

*Nuclear plant operators rely on instruments for information on plant operating state. The introduction of new, computer-based systems—such as the safety parameter display system (SPDS), which shows safety-related information on color CRT screens—makes the reliability of existing instrumentation critical. Enhancement of signal reliability and efficient use of current signal diversity with the powerful new process computers are topics of EPRI research. Projects focus on reducing instrument-related problems in nuclear power plants by combining traditional signal validation methods with techniques based on analytic relationships among key plant variables.*

EPRI selected SPDS as the system for demonstrating signal validation research results. Working with Northeast Utilities Service Co. and General Public Utilities (GPU), EPRI plans to add signal validation software to SPDSs currently installed in the Millstone-3 and Oyster Creek power plants.

Without an SPDS, operators must perform three tasks during an abnormal situation: evaluate signal quality, interpret the signals to assess plant status, and take corrective action. Signal validation helps operators in the first task; SPDS helps in the second task; and together, they allow operators to concentrate on the third task—to control and bring the plant to a safe state.

### Methodology

Operators usually rely on judgment to detect signal abnormalities. They compare redundant gages and diverse indications with their mental model of plant behavior. Today's powerful plant computers promise relief by providing automatic aids for validating signals. Systems such as SPDSs can then be made robust enough to reduce false alarms and provide highly reliable information. Such robustness can be ensured by on-line signal validation methods—computerized procedures for (1) verifying the accuracy of individual signals received from various plant instruments, and (2) providing a single measure for each key variable for use in plant safety monitoring and control.

The most common signal validation practices in the nuclear industry today are limited to a few rather simple techniques that rely, for the most part, on process symmetry and physical redundancy. These techniques include such methods as sensor comparison, limit checking, auctioneering, instrument-loop integrity checking, and calibration checking. In 1980 EPRI initiated a feasibility study of parity-space and analytic redundancy techniques (NP-2110), and since then, many articles on improved signal validation practices in power plants have appeared in the literature.

The parity-space technique focuses on measurement inconsistencies, taking into account such usual signal characteristics as bias, drifts, and failures; it serves as a failure detection tool. Analytic redundancy is a means of supplementing hard-wired measurements with an approximated software measurement when existing instrumentation is inadequate. These two kinds of techniques are widely used in the aerospace industry. Now researchers in EPRI projects are applying them (with improvements) to validate key variables in BWRs and PWRs.

The parity-space algorithm tests the consistency of a given variable's measurements in order to detect and isolate faults; the parity vector grows in the direction associated with a failed sensor. The technique estimates the variable as a weighted average of the consistent sensor measurements. Consistency is defined relative to an acceptable error magnitude for each measurement. The methodology does not require detailed knowledge of sensor and plant noise statistics; the test is embodied in a generic code unit called a decision/estimator (D/E).

A D/E performs two functions. First, it decides which inputs are consistent and to what degree. Second, it detects, identifies, and isolates failed instruments by generating a validated estimate. Two EPRI reports document the mathematical basis for this code unit (NP-2110 and NP-3641).

Another kind of generic model, an analytic redundancy model (ARM), measures a variable by means of the physical relationships among other variables. Such models use functionally diverse data to generate a signal output, an analytic measurement. ARMs are introduced for several reasons. First, the redundancy of identical, colocated sensors may be insufficient for the D/E fault detection and isolation (FDI) function. In such cases, ARMs will enable the use of other sensors to supplement inadequate direct or physical redundancy. Second, ARMs can provide a measure of common-cause rejection by synthesizing a signal from functionally diverse sensors. ARMs can generate signals that are not instrumented or that are difficult to observe.

An ARM correlates mass, momentum, and energy conservation, hardware operating characteristics, and other empirical data. It is a low-order model, unrestricted by linearity, and may contain parameters fitted to plant sensor data either off-line (tested under simulated conditions before implementation in real-time situations) or adaptively (built-in flexibility to adapt to changing conditions in real time). Because ARMs are sensor-driven and limited in scope, fairly simple models suffice to give good fidelity. If the interval for updating sensor data is short relative to process time constants, then a static model can be used even in transient operation.

The D/E is the core of the FDI logic. It is programmed as a generic software unit in which two or more data sources are merged into a single data output. Further, it incorporates a rule-based decision logic. The data sources may have different ranges and accuracies and may be any of three types: sensors, another D/E, or an ARM.

The term *signal* applies to these data sources, and the term *validated output* applies to D/E output. Because all signals originate from sensors, they contain bias and scale-factor errors with respect to the values of the plant variables. Some signals may be out of range, and others may be failed at some particular sample time. (A failed signal is one that departs significantly and/or abruptly from previous estimates, given the normal bias and scale-factor errors.)

Because providing some information at the output of a D/E under all circumstances is important, it is necessary to consider a number of logical cases and provide rule-based alternatives for different applications.

Although consistency between sensor measurements is determined solely by immediate observations, fault declaration and removal of an input is based on a sequential test that uses cumulative information from past and current samples. This process keeps error bounds small enough to minimize the probability of missed alarms and, at the same time, prevent excessive false alarms from spurious noise, modeling error, and miscalibration.

The signal validation process can be represented in terms of information flow. The plant sensor–generated information flows through a structure of D/Es and ARMs. How the particular D/Es and ARMs are set up is a function of plant configuration, sensor signal availability on the process computer, and design requirements. Figure 1 shows an example for pump signal validation. The objective in this case is to obtain a valid flow measurement, using physical and validated measurements. Sensor signals for pump flow, speed, suction pressure, and discharge pressure constitute the input to the validation system, which features four D/Es and a pump ARM.

Information from actual measurements is given higher weight than analytic measurements in estimating. When there are adequate sensors, as for the pump discharge pressure in the example, analytic models may not be necessary, and sensor comparison with the D/E's rule-based logic improves sensor fault detection.

Parity-space and analytic redundancy techniques were first demonstrated in the steam generator–feedwater subsystem at Baltimore Gas & Electric Co.'s Calvert Cliff Unit 1 (NP-2110). The signal validation flow diagram and the models were developed to isolate failures at the sensor level as well as the component level. A computer code developed by the contractor, Combustion Engineering, Inc. (C–E), calculated the test cases for models that represented the subsystem behavior during steady-state and transient conditions. The subsystem variables were corrupted with typical, uniformly distributed sensor noise to simulate sensor output. The study demonstrated the feasibility of the methodology for detecting common-mode failures, bias, scale-factor errors, and sticking values.

### BWR applications

The signal validation methodology and the software developed in the feasibility study were first applied to sensors that monitor BWR suppression pool parameters at GPU's Oyster Creek plant. As an outcome of this effort, contractors C. S. Draper Laboratories and Nutech Engineers have developed a real-time signal validation program to validate signals from suppression pool temperature, level, and pressure sensors, including the status of the safety/relief valves (RP2448-1). The top-level architecture developed accommodates both the current and planned upgrades to pool instrumentation and provides a single validated measure for the bulk temperature. The signal validation was tested by using cases constructed from RETRAN and CONTEMPT code runs and the steady-state data from the plant (NP-3641).

The suppression pool temperature is an important safety parameter in BWRs, and operators use it to initiate various actions, such as suppression pool cooling, scram, and depressurization, as determined by the emergency operating procedures. The real-time signal validation program for monitoring BWR sensors developed during this study offers the following potential benefits.

- Reduces the probability of mistakes, such as delayed initiation of residual heat removal or inadvertently actuating heat removal on the basis of inadequate indications
- Increases plant availability by allowing the plant to continue operating with fewer or failed sensors
- Reduces the need for additional instrumen-

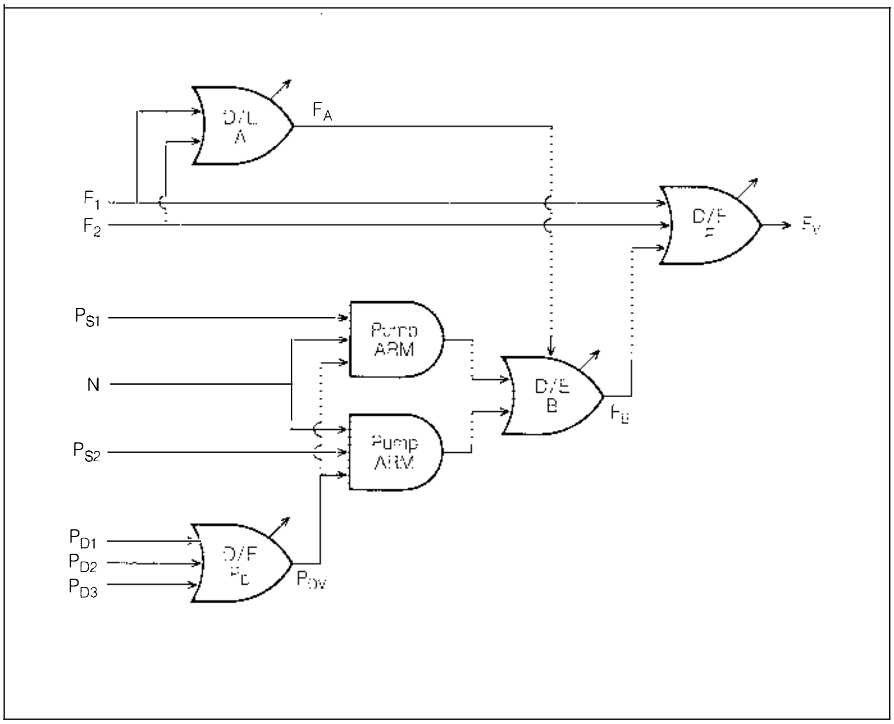
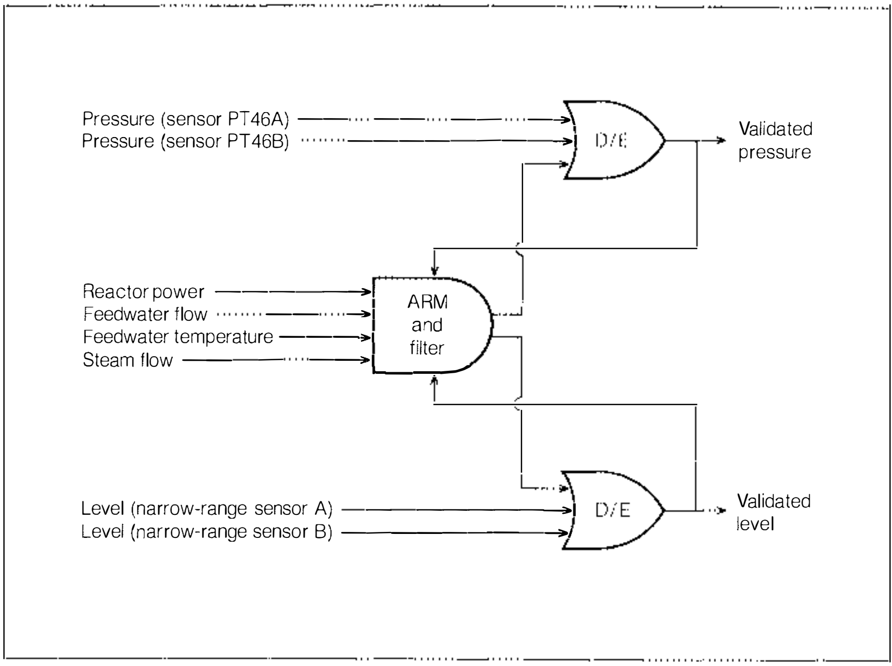



Figure 1 Pump signal validation. One D/E uses signals from two pump flow sensors ($F_1$ and $F_2$) to produce an intermediate estimate of flow ($F_A$). A second D/E uses signals from three pump discharge pressure sensors ($P_{D1}$, $P_{D2}$, and $P_{D3}$) to derive a validated discharge pressure measurement ($P_{DV}$). This value is input into a pump ARM, which uses it along with signals from two pump suction pressure sensors ($P_{S1}$ and $P_{S2}$) and a pump speed sensor (***N***) to derive another set of flow estimates. A third D/E uses these estimates and the $F_A$ estimate to produce still another, improved flow estimate ($F_B$). A final D/E compares the $F_B$ estimate with the $F_1$ and $F_2$ sensor signals to produce a single validated flow measurement ($F_V$). In addition to producing an estimate or a validated measurement, each D/E also provides output information on measurement inconsistencies and component failure diagnostics.

Figure 2 Oyster Creek BWR vessel level and pressure validation. The ARM uses six signals and gives the third input necessary for the D/Es to validate the level and pressure. The two validated parameter values are fed back into the ARM as input for the next time sample calculations and for self-checking.




tation, such as may be required by Regulatory Guide 1.97, NUREG-0783, and NUREG-0661

- Detects some common-cause failures by diverse analytic and direct measurements of suppression pool bulk temperatures, relief valve positions, and cooling flow rates.

EPRI is currently applying signal validation to other key parameters, using Oyster Creek as the reference plant. The major part of this effort is to validate BWR vessel level inside and outside the core shroud. Figure 2 depicts the Oyster Creek vessel level and pressure signal validation procedure.

The variables used in the suppression pool and BWR vessel level validation are combined into a single library of software modules that would validate signals for major Oyster Creek plant variables. The variables validated are flow through the reactor core; core neutron flux and spray-system flow; reactor vessel level and pressure; suppression pool level; drywell pressure, temperature, and sump level; emergency relief valve positions; containment building pressure; mode switch; scram demand; and isolation demand.

Measurements used in the validation designs were taken from lists of inputs to the plant computer or were derived from the Oyster Creek piping and instrumentation diagrams. Three of Commonwealth Edison Co.'s BWRs also contributed information in developing this generic software library.

**PWR applications**

Working with nine utilities, EPRI developed a list of 18 key variables for which signal validation is necessary. Such validation would support the critical safety functions used in the SPDS in operating PWRs. Babcock & Wilcox Co. and C. S. Draper Laboratories are the contractors in this project to develop and test an on-line signal validation software for Westinghouse Electric Corp. and C–E plants (RP2292). The signal validation function requirements and design specifications are complete. The reports summarizing software tests at Northeast Utilities' Millstone-3 and Millstone-2 plants are scheduled for completion in mid 1986 and mid 1987, respectively. The software will be available in modular form, with individual test cases for each plant variable that can be used on the IBM personal computers.

Results in three demonstrations to date have been encouraging. The first validated feed pump instruments and showed the response of validation software to induced instrument failures. The second demonstration used system-level analytic models to infer natural circulation flow rate and cold leg temperature for a Westinghouse plant. That demonstration showed how advanced techniques can independently measure an unmeasured variable. The final demonstration used the modules developed for the Millstone-2 plant. A data acquisition system transmitted simulated data to a process computer. When instrument failures were simulated, the signal validation modules produced the correct response.

The in-plant demonstration of signal validation is at Millstone-3 and Millstone-2. Variables selected for validation that support critical safety functions are reactor coolant hot leg and cold leg temperatures, pressure, and flow; steam generator level and pressure; feedwater flow; neutron flux; pressurizer level; letdown and residual heat removal flow; emergency sump level; containment pressure; core exit temperature; control rod position; subcooling margin; and high- and low-pressure injection flows.

In conclusion, signal validation is an essential element in the development and use of any computer-based operator aid system in nuclear plants. One immediate potential application is the verification of input to SPDSs and plant controllers. Analytic redundancy offers a cost-effective alternative to adding sensor hardware and allows abnormal signal detection in sensors and in components.

In an average PWR with about 30% unavailability, instrument failures alone account for one trip a year per plant, and the average plant shutdown time is about 24 hours. If such trips could be eliminated by sensor validation, utilities could save about $500,000 a year per plant, based on typical replacement power costs for an 800-MW (e) unit for one day. In addition, preventing erroneous sensor information would dramatically reduce unnecessary challenges to plant protection systems, which would significantly enhance safety.

Not only will a sensor validation technique enhance plant safety but it will increase plant availability. Further, the potential of signal validation methods to identify failures of components promises added safety and availability by permitting timely and accurate operator action to alleviate disturbances. *Project Manager: S. Murthy Divakaruni*

## VALVE MOTOR OPERATOR IMPROVEMENTS

*In recent years the reliability of valve motor operators (VMOs) has become an issue of increasing concern to utilities, particularly those with nuclear power plants. An evaluation of the data on VMO failure contained in licensee event reports maintained by the Nuclear Regulatory Commission shows that a majority of the* *failures were in some way attributable to the equipment's electromechanical switches. The difficulty and uncertainty of establishing set points (particularly for torque switches), torque and limit switch unreliability, unsatisfactory protection from motor thermal overload, and personnel unawareness of the mechanical/electromechanical condition of a given VMO contributed to the reported failures. In response to this situation, EPRI initiated a project to establish methods for correcting deficiencies in VMOs (RP2233-2).*

The project has led to the development of a microprocessor-based control and diagnostics system that alleviates many of the problems related to the performance of conventional VMOs. The new system has several advantages. It eliminates dependency on conventional electromechanical torque and limit switches. It provides easy, accurate set point adjustment for position control, stem load control, predictive control of performance variables, and motor overload protection. In addition, it provides an easily interpreted graphic display of important control system parameters and informs operating personnel of

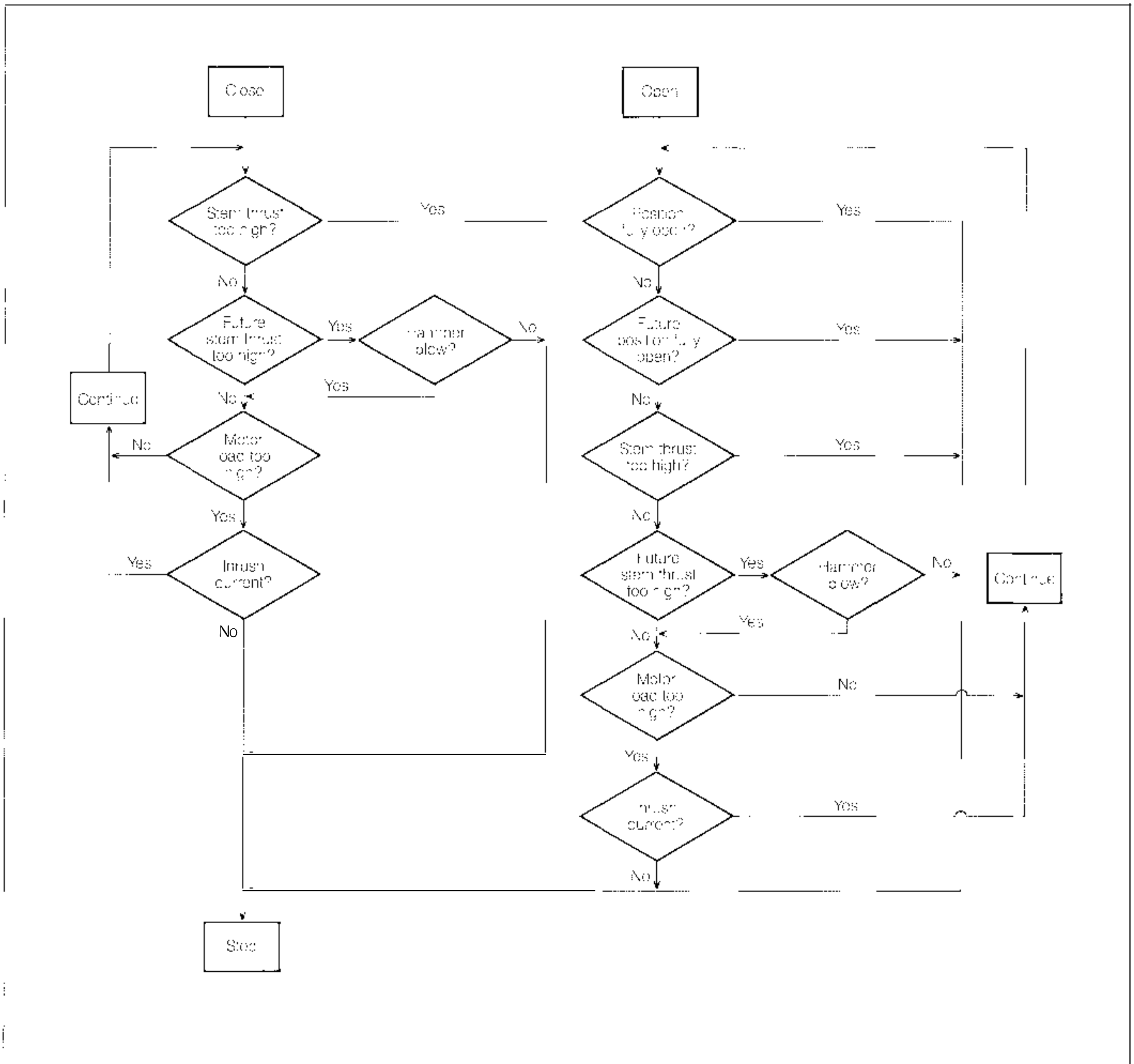
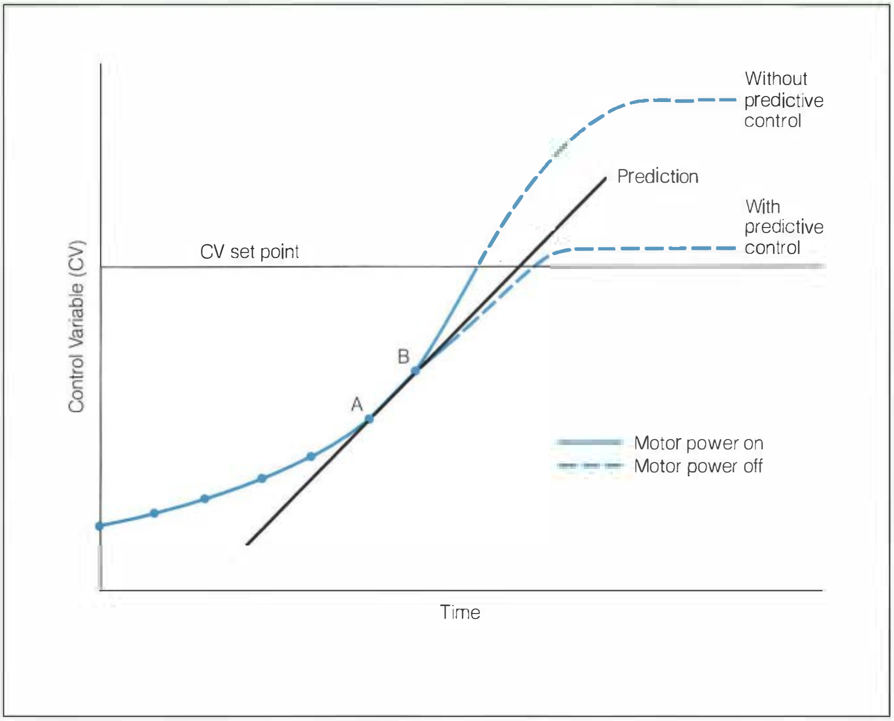



Figure 3 Control algorithm for the VMO microprocessor-based control system. In the valve-closing direction, stem thrust is the primary control variable; in the valve-opening direction, stem position.

Figure 4 On the basis of data obtained at regular intervals, the VMO predictive control feature determines whether a preselected set point is being approached too rapidly and makes adjustments as appropriate. Without predictive control in this example, the VMO is not tripped until the set point value is reached, and rotational inertia results in considerable overshooting of that value. With predictive control, the system trips the VMO earlier because a prediction based on data at points *A* and *B* has provided a warning of the situation; overshooting of the set point is thus minimized.




changing operational characteristics. This last feature is of particular significance because it allows both an instantaneous evaluation of the VMO and a diagnosis of abnormal performance.

The microprocessor control and diagnostic system uses data on valve position, valve stem load, motor voltage, motor current, and the phase angle between the current and voltage waveforms. It continuously evaluates this information according to an algorithm to control VMO functioning (Figure 3). The system also has a predictive control feature (Figure 4). By sensing the rate at which a set point is about to be reached, the system can be adjusted to trip the VMO before the set point is actually attained. This feature minimizes stem thrust overshoot caused by rotational inertia that occurs in fast-closing valves. Variations in the control algorithm are readily achieved by assigning different priorities to control of the valve.

Valve stem thrust data are provided to the microprocessor system on the basis of a calibration (established when the system is set up) between measured stem thrust and measured spring pack deflection. Spring pack deflection actuates the torque switch in the existing VMO. This calibration method is equivalent to that used in installing temporary VMO diagnostic systems, such as the motor-operated valve analysis and test system (MOVATS, Inc., Marietta, Georgia).

The microprocessor system design facilitates system installations in existing power plants. The system can be installed directly at the valve, at the associated motor control center, or at the main control board. It requires a reliable source of 120-Vac power, as well as input data from the valve and the motor power supply. If the VMO to be controlled is inside the reactor containment and the microprocessor system is located at the motor control center outside the containment, two pairs of twisted control wires, in addition to wiring already in place, would be needed to transmit input data on valve position and valve stem load. All other input data and the power source are normally available at the motor control center. The addition of this control wiring may require new penetration of the containment.

EPRI's contractor, Foster-Miller, Inc., has constructed a prototype system and is demonstrating its performance in shop tests. EPRI is negotiating with interested utilities for in-plant demonstration of the system. An interim report on work to date is available (NP-4254). *Project Manager: Boyd Brooks*

# New Technical Reports

Each issue of the *Journal* includes information on EPRI's recently published reports.

Inquiries on technical content may be directed to the EPRI project manager named at the end of each entry: P.O. Box 10412, Palo Alto, California 94303; (415) 855-2000.

Requests for copies of specific reports should be directed to Research Reports Center, P.O. Box 50490, Palo Alto, California 94303; (415) 965-4081. There is no charge for reports requested by EPRI member utilities, government agencies (federal, state, local), or foreign organizations with which EPRI has an agreement for exchange of information. Others in the United States, Mexico, and Canada pay the listed price. Overseas price is double the listed price. Research Reports Center will send a catalog of all EPRI reports on request.

EPRI also has a report summary program available without charge to members and by subscription to nonmembers. Each summary provides a concise one-page description of the published report. For information on how to order report summaries, please contact the EPRI Technical Information Division, P.O. Box 10412, Palo Alto, California 94303; (415) 855-2411.

## ADVANCED POWER SYSTEMS

**Evaluation of Coal-Derived Liquids as Boiler Fuels**

AP-3985 Final Report (RP2112-2, -9); Vol. 1, $32.50; Vol. 2, $32.50; Vol. 3, $32.50; Vol. 4, $25.00; Vol. 5, $40.00
Contractors: Southern Company Services, Inc.; W. J. Keane and Associates, Inc.
EPRI Project Manager: H. Schreiber

**Dynamic Simulation Models for Selective Sulfur Removal in Coal Gasification Systems**

AP-4106 Final Report (RP1038-6); $32.50
Contractor: Hyprotech, Ltd.
EPRI Project Manager: G. Quentin

**Technology Assessments of Advanced Power Generation Systems**

AP-4173 Final Report (RP2387-1); $25.00
Contractor: Coecorp
EPRI Project Managers: A. Cohn, L. Angello, W. Rovesti

**Effects of Amine Solvents and Oxygen Functionalities on Coal Liquefaction**

AP-4176 Interim Report (RP2147-5); $32.50
Contractor: SRI International
EPRI Project Manager: L. Atherton

**Proceedings: Fourth Annual EPRI Contractors' Conference on Coal Gasification**

AP-4177 Proceedings (RP1654); $55.00
EPRI Project Managers: N. Holt, G. Quentin

**Integrated Two-Stage Coal Liquefaction Studies**

AP-4193 Final Report (RP2147-3); $55.00
Contractor: University of Wyoming
EPRI Project Manager: N. Stewart

**Evaluation of Protective Coatings for Hot Components of Combustion Turbines**

AP-4194 Final Report (RP2388-3); $32.50
Contractor: Southwest Research Institute
EPRI Project Manager: R. Viswanathan

**Wellhead-Sized Binary-Cycle Geothermal Power Plants**

AP-4198 Final Report (RP2501-1); $47.50
Contractor: Fluor Engineers, Inc.
EPRI Project Manager: B. Louks

**Wind Power Stations: 1984 Performance and Reliability**

AP-4199 Interim Report (RP1996-2); $32.50
Contractor: R. Lynette & Associates, Inc.
EPRI Project Manager: F. Goodman

**Theory on Trace Arsenic in Geothermal Fluids**

AP-4214 Final Report (RP1525-6); $25.00
Contractor: James W. Cobble
EPRI Project Manager: M. McLearn

**Availability Analysis Handbook for Coal Gasification and Combustion Turbine–Based Power Systems**

AP-4216 Final Report (RP1800-1); $40.00
Contractor: Arinc Research Corp.
EPRI Project Manager: J. Weiss

**Selective Hydrogenation of Polynuclear Heteroatomic Compounds**

AP-4227 Final Report (RP2147-7); $25.00
Contractor: Lawrence Berkeley Laboratory
EPRI Project Manager: L. Atherton

**MOD-2 Wind Turbine Field Experience in Solano County, California**

AP-4239 Final Report (RP1996-3); $40.00
Contractor: Pacific Gas and Electric Co.
EPRI Project Manager: F. Goodman

**Testing and Evaluation of a 500-kW Vertical-Axis Wind Turbine**

AP-4258 Interim Report (RP1590-3); $32.50
Contractor: Southern California Edison Co.
EPRI Project Manager: F. Goodman

**Variable Rotor Speed for Wind Turbines: Objectives and Issues**

AP-4261 Final Report (RP1996-9); $25.00
Contractor: Power Technologies, Inc.
EPRI Project Manager: F. Goodman

## COAL COMBUSTION SYSTEMS

**Atmospheric Fluidized-Bed Combustion Utility Boiler: Conceptual Design Assessment**

CS-4127 Final Report (RP718-2, 722-2); $40.00
Contractor: Babcock & Wilcox Co.
EPRI Project Manager: S. Tavoulareas

**Manual on the Use of Flue Gas Conditioning for ESP Performance Enhancement**

CS-4145 Final Report (RP724-2); $32.50
Contractor: Southern Research Institute
EPRI Project Manager: R. Altman

**Hot-Side Electrostatic Precipitator Flue Gas Conditioning: Fire-Side Corrosion Studies at Lansing Smith Plant**

CS-4149 Final Report (RP644-4); $25.00
Contractor: Southern Research Institute
EPRI Project Managers: J. Stringer, R. Altman

**Pilot Study of Flakt-Boliden Desulfurization Process**

CS-4153 Final Report (RP1258-2); $40.00
Contractor: Stearns Catalytic Corp.
EPRI Project Manager: D. Stewart

**Feedwater Heater Procurement Guidelines**

CS-4155 Final Report (RP1887-1); $47.50
Contractor: Joseph Oat Corp.
EPRI Project Managers: R. Coit, I. Diaz-Tous

**Impact of Modularity on Utility Investment Decisions: Implications for Turbocharged-Boiler Technologies**

EA/CS-4158 Final Report (RP1432-1-2, RP1432-3-2); $25.00
Contractors: Applied Decision Analysis, Inc.; Decision Focus, Inc.
EPRI Project Managers: S. Chapel, S. Drenker

**Sumner County Solid-Waste Energy Recovery Facility**

CS-4164 Final Report (RP2190-2); Vol. 1, $32.50; Vol. 2, $25.00
Contractor: Tennessee Valley Authority
EPRI Project Manager: C. McGowin

**Portable Gas Chromatograph for Polychlorinated Biphenyl (PCB) Analysis**

CS-4175 Final Report (RP1263-9); $25.00
Contractor: S-Cubed
EPRI Project Manager: R. Komai

**Proceedings: First Joint Symposium on Dry $SO_2$ and Simultaneous $SO_2/NO_x$ Control Technologies**

CS-4178 Proceedings (RP2533-3); Vol. 1, $55.00; Vol. 2, $47.50
Contractor: Acurex Corp.
EPRI Project Manager: M. McElroy

**Literature Survey: Suction Effects on Feedpump Performance**

CS-4204 Interim Report (RP1884-10); $32.50
Contractor: Sulzer Brothers Ltd.
EPRI Project Manager: S. Pace

**Proceedings: Fossil Plant Life Extension Conference and Workshop**

CS-4207 Proceedings (RP1862-3); $62.50
Contractor: Bechtel Power Corp.
EPRI Project Manager: J. Scheibel

**$SO_2$ and $NO_x$ Retrofit Control Technologies Handbook**

CS-4277-SR Special Report; $55.00
EPRI Project Manager: M. Miller

**Detection of Water Induction in Steam Turbines: Field Demonstration**
CS-4285 Final Report (RP637-2); $32.50
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: T. McCloskey

## ELECTRICAL SYSTEMS

**Assessing Quasi-linearization and Kalman Filtering in the Determination of Stability Study Constants for Utility Operating Generators**
EL-3903 Final Report (RP1999-5); $47.50
Contractor: Ohio University
EPRI Project Manager: D. Sharma

**On-line Incipient Fault Detector**
EL-4002 Final Report (RP748-1); $25.00
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: E. Norton

**Acoustic Emission Detection of Partial Discharges in Power Transformers**
EL-4009 Final Report (RP426-1); $32.50
Contractor McGraw-Edison Co.
EPRI Project Manager: S. Nilsson

**Evaluation of Procedures for Predicting Foundation Uplift Movements**
EL-4107 Final Report (RP1493-4); $32.50
Contractor: Cornell University
EPRI Project Manager: V. Longo

**Forced Convective Cooling of a Distribution Transformer With an Electrohydrodynamic Dielectric Pump**
EL-4108 Final Report (TPS82-635); $25.00
Contractor: General Electric Co.
EPRI Project Manager: J. Porter

**Wood Pole Properties: Background and Southern Pine Data**
EL-4109 Interim Report (RP1352-2), Vol. 1; $32.50
Contractor: Research Institute of Colorado
EPRI Project Manager: P. Lyons

**High-Voltage DC Circuit Breaker Experiment**
EL-4138 Final Report (RP1507-1); $32.50
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: J. Porter

**Polysil Structures**
EL-4181 Final Report (RP2015-1); $32.50
Contractor: Hughes Supply, Inc.
EPRI Project Manager: J. Dunlap

**Fault Current Limiters: Laboratory Investigations**
EL-4186 Final Report (RP993-1); $32.50
Contractor: State University of New York at Buffalo
EPRI Project Manager: J. Porter

**Development of a Fault Current Limiter Using Vacuum Arc Fault Current Commutation**
EL-4187 Final Report (RP564-4); $25.00
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: J. Porter

**Component Evaluation Unit for Remote Maintenance of Transmission Lines**
EL-4188 Interim Report (RP1497-1); $25.00
Contractor: Southwest Research Institute
EPRI Project Manager: J. Dunlap

**Transient Stability Program Output Analysis**
EL-4192 Final Report (RP2206-3); $25.00
Contractor: Iowa State University
EPRI Project Manager: J. Mitsche

**Long-Life Cable Development: Cable-Processing Survey**
EL-4201 Final Report (RP2438-1); $25.00
Contractor: Battelle, Columbus Laboratories
EPRI Project Manager: B. Bernstein

**Electromagnetic Transients Program (EMTP) Primer**
EL-4202 Final Report (RP2149-1); $40.00
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: J. Mitsche

**The Mixture of Normals Approximation of Equivalent Load Duration Curves**
EA/EL-4266 Final Report (RP1808-3); $32.50
Contractor: Pacific Gas and Electric Co.
EPRI Project Manager: J. Delson

**Improved Motors for Utility Applications: Industry Assessment Study—Update and Analysis**
EL-4286 Final Report (RP1763-2), Vol. 1; $32.50
Contractor: General Electric Co.
EPRI Project Manager D. Sharma

## ENERGY ANALYSIS AND ENVIRONMENT

**Case Studies: Technology Choice**
EA-3619 Final Report (RP1433-1); Vol. 3, $32.50; Vol. 4, $25.00
Contractor: Woodward-Clyde Consultants
EPRI Project Manager: L. Rubin

**Groundwater Data Analyses at Utility Waste Disposal Sites**
EA-4165 Final Report (RP2283-2); $55.00
Contractor: Tetra Tech, Inc.
EPRI Project Manager: I. Murarka

**Integrated Fuels and Investment Planning**
EA-4166 Final Report (RP2372); $32.50
Contractors: Dames & Moore; Putnam, Hayes & Bartlett, Inc.
EPRI Project Managers: J. Platt, S. Mukherjee

**Input-Output Analysis of Occupational Health Risks in Electric Power Generation**
EA-4171 Final Report (RP1772-2); $25.00
Contractor: Energy and Resource Consultants, Inc.
EPRI Project Manager: P. Ricci

**Foreign Uranium Supplies for the United States**
EA-4180 Final Report (RP883-3); $32.50
Contractor: Nuclear Resources International, Inc.
EPRI Project Manager: J. Platt

**Design, Construction, and Testing of a DC Bioeffects Enclosure for Small Animals**
EA-4189 Final Report (RP1774-1); $32.50
Contractor: Battelle, Pacific Northwest Laboratories
EPRI Project Manager: R. Patterson

**Proceedings: Buildings and Their Energy Systems—Technologies and Planning Strategies**
EA/EM-4197 Proceedings (RP2034-12); $47.50
Contractor: Policy Research Associates, Inc.
EPRI Project Managers: J. Wharton, G. Purcell, O. Zimmerman

**Field Air-Exclusion System for Measuring the Effects of Air Pollutants on Crops**
EA-4203 Final Report (RP1908-3); $32.50
Contractor: University of California at Riverside
EPRI Project Manager: J. Huckabee

**Estimating Response to Time-of-Use Rates: Implications of the Homothetic Separability Assumption**
EA-4205 Final Report (RP1008-7); $25.00
Contractor: Richard W. Parks
EPRI Project Manager: A. Faruqui

**Commercial and Industrial Response to Time-of-Use Rates: Methodology and Case Studies**
EA-4206 Final Report (RP2043-1); $47.50
Contractor: Research Triangle Institute
EPRI Project Manager: A. Faruqui

**Leaching Studies on Utility Solid Wastes: Feasibility Experiments**
EA-4215 Final Report (RP2485-4); $47.50
Contractor: Arthur D. Little, Inc.
EPRI Project Manager: I. Murarka

**Extra-High-Voltage Transmission Lines: Mechanisms of Biological Effects on Honeybees**
EA-4218 Final Report (RP934-1, -2); $25.00
Contractor: Bioconcern
EPRI Project Manager: R. Patterson

**Setting Objectives for Demand-Side Management: Topic Report 1**
EA-4220 Interim Report (RP2548-1); $25.00
Contractors: Temple, Barker & Sloane, Inc.; Battelle, Columbus Laboratories
EPRI Project Managers: D. Geraghty, A. Faruqui

**Spatial Variability of Soil & Physical Parameters in Solute Migration: A Critical Literature Review**
EA-4228 Interim Report (RP2485-6); $25.00
Contractor: University of California at Riverside
EPRI Project Manager: I. Murarka

**Feasibility of Physical Hydraulic Modeling of Groundwater Pollutant Transport**
EA-4229 Final Report (RP2280-2); $32.50
Contractor: Clemson University
EPRI Project Manager: I. Murarka

**Sample Designs for Load Research: The Bootstrap Comparison Procedure**
EA-4232 Final Report (RP1816-3); $32.50
Contractor: Applied Management Sciences, Inc.
EPRI Project Manager: E. Beardsworth

**The Mixture of Normals Approximation of Equivalent Load Duration Curves**
EA/EL-4266 Final Report (RP1808-3); $32.50
Contractor: Pacific Gas and Electric Co.
EPRI Project Manager: J. Delson

**Field Measurement Methods for Hydrogeologic Investigations: A Critical Review of the Literature**
EA-4301 Final Report (RP2485-7); $47.50
Contractor: Residuals Management Technology, Inc.
EPRI Project Manager: I. Murarka

## ENERGY MANAGEMENT AND UTILIZATION

**Survey of Heat Pump Service Life**
EM-4163 Final Report (RP2417-1); $25.00
Contractor: Alabama Power Co.
EPRI Project Manager: C. Hiller

**Parametric Analysis of a 6500-Btu/kWh Heat Rate Dispersed Generator**
EM-4179 Final Report (RP1041-12); $32.50
Contractors: Energy Research Corp.; Fluor Engineers, Inc.
EPRI Project Manager: E. Gillis

**Proceedings: Buildings and Their Energy Systems—Technologies and Planning Strategies**
EA/EM-4197 Proceedings (RP2034-12); $47.50
Contractor: Policy Research Associates, Inc.
EPRI Project Managers: J. Wharton, G. Purcell, O. Zimmerman

**Design and Cost of Standardized Lead-Acid Battery Systems for Utility Energy Management**
EM-4200 Final Report (RP1275-12); $25.00
Contractor: Bechtel Group, Inc.
EPRI Project Manager: J. Birk

**Economic Feasibility of Energy Storage for Rural and Municipal Utilities**
EM-4234 Final Report (RP1832-3); $32.50
Contractor: Burns & McDonnell Engineering Co.
EPRI Project Manager: T. Yau

**Technoeconomic Evaluation of Large-Scale Electrolytic Hydrogen Production Technologies**
EM-4256 Final Report (RP1086-18); $32.50
Contractor: Stone & Webster Engineering Corp.
EPRI Project Manager: B. Mehta

**Utility Cycle Testing of a 500-kWh Zinc Chloride Battery at the Battery Energy Storage Test (BEST) Facility**
EM-4295 Final Report (RP255-2); $25.00
Contractor: Public Service Electric & Gas Co.
EPRI Project Manager: W. Spindler

## NUCLEAR POWER

**On-line Ion Chromatography at Three PWRs**
NP-4121 Interim Report (RP1447-1); $32.50
Contractor: General Electric Co.
EPRI Project Manager: T. Passell

**Radionuclide Scrubbing in Water Pools: Gas-Liquid Hydrodynamics**
NP-4154 Final Report (RP2117-1), Vol. 1; $40.00
Contractor: Battelle, Columbus Laboratories
EPRI Project Manager: R. Oehlberg

**BWR Coolant Impurity Identification**
NP-4156 Final Report (RP2058-11); $25.00
Contractor: General Electric Co.
EPRI Project Manager: J. Nelson

**Prototype Evaluation: Westinghouse PHOCUS Boresonic System**
NP-4167 Final Report (RP1570-2); $25.00
Contractor: J. A. Jones Applied Research Co.
EPRI Project Manager: G. Dau

**Dominant Contributors to Seismic Risk: An Appraisal**
NP-4168 Final Report (RP2170-5); $25.00
Contractor: NTS/Structural Mechanics Associates
EPRI Project Manager: D. Worledge

**Effect of Feedwater Oxygen Control at the Vermont Yankee BWR**
NP-4169 Topical Report (RP1934-1); $32.50
Contractor: NWT Corp.
EPRI Project Managers: M. Naughton, C. Wood

**Influence of Dissolved Hydrogen and Oxygen on Crack Growth in LWR Materials**
NP-4183M Final Report (RP1930-3); $25.00
Contractor: General Electric Co.
EPRI Project Manager: J. Gilman

**PWR Fuel Performance Program**
NP-4196 Final Report (RP611-1); $25.00
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: A. Machiels

**Longevity of Nuclear Power Systems**
NP-4208 Final Report (SIA84-421-1); $32.50
Contractor: Oak Ridge Associated Universities
EPRI Project Manager: J. Carey

**Additives for pH Control in PWR Secondary Water**
NP-4209 Interim Report (RP1571-3); $32.50
Contractor: San Diego State University
EPRI Project Manager: T. Passell

**Conceptual Study to Develop Revised Dynamic Code Criteria for Nuclear Power Plant Piping**
NP-4210 Final Report (RP1543); $32.50
Contractor: Impell Corp.
EPRI Project Manager: S. Tagart

**BWR Cobalt Deposition Studies**
NP-4236 Interim Report (RP2295-3); $25.00
Contractor: General Electric Co.
EPRI Project Manager:C. Wood

**Neutron Energy Spectra in the Core and Cavity of the ANO-2 PWR**
NP-4238 Topical Report (RP827-4); $25.00
Contractor: University of Missouri at Rolla
EPRI Project Manager: T. Passell

**Decontamination Waste Management**
NP-4240 Final Report (RP2296-8); $25.00
Contractor: Chem-Nuclear Systems, Inc.
EPRI Project Manager: C. Wood

**EPRI Projects on Power Plant Steam-Cycle Water Chemistry**
NP-4241-SR Special Report; $25.00
EPRI Project Manager: C. Wood

**Analytic Simulator Qualification Methodology**
NP-4243 Final Report (RP2054-1); $47.50
Contractor: Babcock & Wilcox Co.
EPRI Project Manager: J. Sursock

**Sensitivity of a Reactor Coolant Pump Seal to Changes of Operating Conditions**
NP-4244 Interim Report (RP1556-3); $25.00
Contractor: Atomic Energy of Canada Ltd.
EPRI Project Manager: F. Gelhaus

**Factors Affecting Wear Damage to Elastomer Seals in Main Coolant Pump Face Seals**
NP-4245 Final Report (RP1556-3); $25.00
Contractor: Atomic Energy of Canada Ltd.
EPRI Project Manager: F. Gelhaus

**CORA-II Model of PWR Corrosion-Product Transport**
NP-4246 Interim Report (RP825-2); $32.50
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: R. Shaw

**Evaluation of Chemical Decontamination Processes for TMI-2 Reactor Coolant Systems**
NP-4260 Interim Report (RP2012-8); $32.50
Contractor: Pacific Nuclear Services
EPRI Project Manager: R. Shaw

**Failures Related to Surveillance Testing of Standby Equipment: Diesel Generators**
NP-4264 Final Report (RP2471-1), Vol. 2; $25.00
Contractor: Mollerus Engineering Corp.
EPRI Project Manager: G. Shugars

**Simulation of Intergranular Attack on Alloy 600 Tubing in Tubesheet Crevices**
NP-4272 Final Report (RPS302-3); $32.50
Contractor: Combustion Engineering, Inc.
EPRI Project Manager: S. Hobart

**Assessment of the COMMIX-1A Code for Analysis of Pressurized Thermal Shock**
NP-4275-SR Special Report; $32.50
EPRI Project Manager: J. Kim

**Assessment of PWR Waterside Corrosion Models and Data**
NP-4287 Final Report (RP1250-7); $32.50
Contractor: Atomic Energy of Canada Ltd.
EPRI Project Manager: A. Machiels

ELECTRIC POWER RESEARCH INSTITUTE
Post Office Box 10412, Palo Alto, California 94303

NONPROFIT ORGANIZATION
U.S. POSTAGE
**PAID**
PERMIT NUMBER 173
MILPITAS, CALIFORNIA

December 1985

**EPRI JOURNAL**

**ADDRESS CORRECTION REQUESTED**