Thin-Film Photovoltaics

ELECTRIC POWER RESEARCH INSTITUTE

EPRI JOURNAL

MARCH
1989

EPRI JOURNAL is published eight times each year (January/February, March, April/May, June, July/August, September, October/November, and December) by the Electric Power Research Institute.

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
David Boutacoff, Feature Writer
Eugene Robinson, Technical Editor
Mary Ann Garneau, Production Editor
Jean Smith, Staff Assistant

Richard G. Claeys, Director
Corporate 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

Please include the code number on your mailing label with correspondence concerning subscriptions.

Cover: An increasing array of products powered by thin-film photovoltaics are entering the commercial marketplace. (Photos courtesy of ARCO Solar, Chronar, and Solarex)

Getting Down to Business With Thin Films

Over the past several years, a growing sense of optimism about photovoltaic power has emerged at EPRI. Since the early 1980s, EPRI's solar power program has advanced a small number of photovoltaic alternatives—always emphasizing fundamental science to achieve high sunlight-to-electricity conversion efficiencies at acceptable cost. EPRI's presence is most evident in its pioneering work on sunlight-concentrating systems with high-efficiency silicon cells. As a result of this major thrust, EPRI has now assumed a leadership position in the sphere of high-concentration photovoltaics.

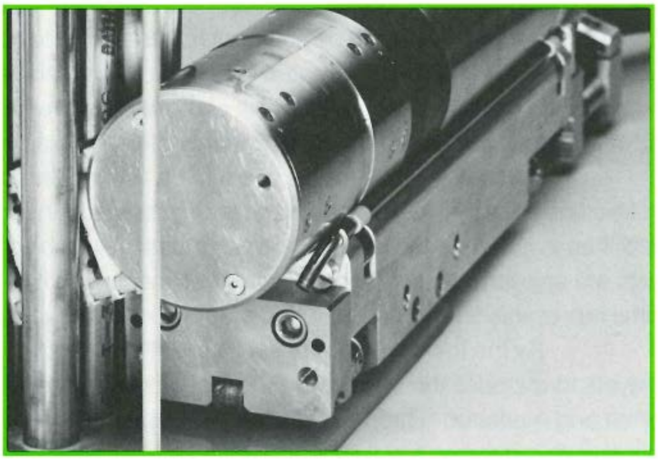
Two other technologies are also advancing toward the bulk power generation market, both based on flat-plate applications without sunlight concentration—crystalline or polycrystalline silicon sheet devices and thin-film devices. Over the past several years, EPRI has initiated fundamental research activities in these areas that are complementary to, and coordinated with, major work under way in the industrial sector. EPRI's strategy of complementing rather than leading reflects the fact that the industrial base in flat-plate photovoltaics is far larger than that in the concentrator arena. This in turn stems from the ability of flat-plate devices to serve in a growing number of cost-effective applications today, with a total worldwide market last year in excess of 30 MW. These relatively simple, nearly maintenance-free devices have found a critical path that is (for the moment at least) less dependent on high efficiencies.

The past five years have seen a continual stream of R&D advances in photovoltaics that have helped substantially to maintain development momentum. However, the continuation of these impressive advancements will not alone be sufficient to sustain photovoltaics for the next five years. Over $2 billion of corporate funds have been invested in photovoltaics, and business is now looking for results. The industry must begin to turn a profit if substantial corporate involvement is to continue. In short, while photovoltaic development has been primarily technology-driven in the past, it is now becoming market-driven as well.

Fortunately, developers seem to be rising to the challenge. Nowhere in the spectrum of photovoltaic activity is the interplay between technology advancement and business development better exemplified than in the area of thin-film systems. Substantial technical advances are occurring regularly, new products are appearing, and the corporate investment picture is fluid. Overall, the expanding market for thin films represents a key near-term hope for ensuring the future of photovoltaics.

As the thin-film industry evolves, EPRI intends to develop partnerships with leading industrial players to expedite the transfer of EPRI technology to the industrial sector, where products are being developed and marketed. Through this route we expect to facilitate the development of truly high-performance photovoltaic systems that will be attractive for energy-significant electric utility use by the latter half of the 1990s.

Edgar A. DeMeo, Manager
Solar Power Program



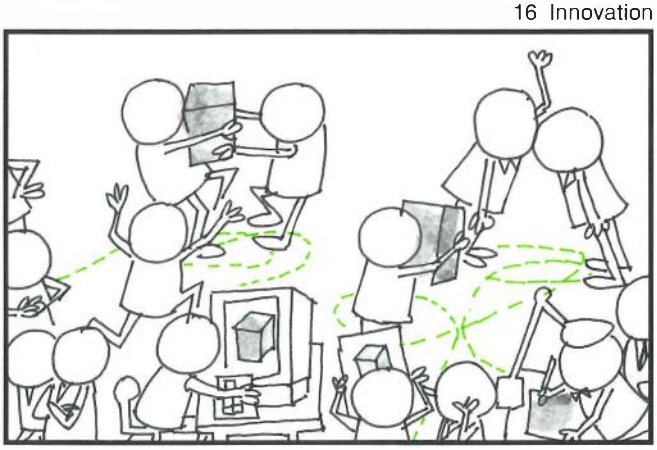
DEPARTMENTS

EPRI JOURNAL

Volume 14, Number 2 March 1989

4 Thin-film PV

16 Innovation



Thin Films: Expanding the Solar Marketplace

Thin-film photovoltaic cells, once relegated to battery-less watches and solar calculators, are moving into more diverse and higher-power markets. A survey of developments and viewpoints reveals a maturing technology that could become a contender for cost-effective bulk power generation.

Across a wide range of electronic technology today, the leading edge is many times thinner than a human hair. Micrometer-thin or thinner films of various semiconductors are at the heart of solid-state devices from video recorder heads and tunable lasers to ultrasensitive detectors and ultrafast microchip switches, including some near-term device prospects for the new high-temperature superconductors.

But perhaps in no other semiconductor application is the potential impact of thin films as great as with the solar cell. The technology of photovoltaics (PV) continues to excite researchers, investors, and the public the world over despite still high, but declining, cost and low, but improving, energy conversion efficiencies.

Low-efficiency thin-film photovoltaic modules are already on the consumer market in solar-powered calculators, patio lights, battery chargers, and remote power gear. If the efforts of many researchers and over a dozen companies in the United States and overseas pan out, thin films eventually will be confirmed as a low-cost route to solar electricity that lights a path to the ultimate market: utility bulk power, with systems ranging in power from kilowatts to megawatts and beyond.

Inexpensive, mass-produced thin-film modules have long been the Holy Grail of photovoltaics, although PV technology first developed along very different lines. In their earliest applications, solar cells made from individual slices of single-crystal silicon powered America's first space satellites in orbit. The same basic crystalline form still accounts for the bulk of an estimated $175-million-a-year worldwide manufacturing industry that now ships about 30 MW of product a year.

Efficiencies for crystalline silicon (Si) are relatively high—28% has been reached in experimental concentrator cells, and 12–14% in commercially available flat-plate solar panels widely used for portable or remote power. Materials requirements and manufacturing equipment and methods, on the other hand, are inherently expensive and are areas where the thin-film approach seems to offer advantages.

Thin films are typically made by vacuum deposition of semiconductor material on a solid substrate, such as glass. Although they must be produced in costly vacuum chambers, thin films have far greater potential for production economies than conventional crystalline silicon, which must be grown into ultrapure ingots, carefully cut into wafers, polished, and mounted in modules. In addition, films require very little semiconductor material and have minimal wastage—the film is grown onto the substrate one layer of atoms at a time. But the potentially low cost of thin-film modules notwithstanding, area-related costs of the other major components of a complete PV power system imply a required minimum sunlight-to-electricity conversion efficiency.

Efficiency has been the sticking point for film technologies. The noncrystalline material that has received the most attention for PV applications, amorphous

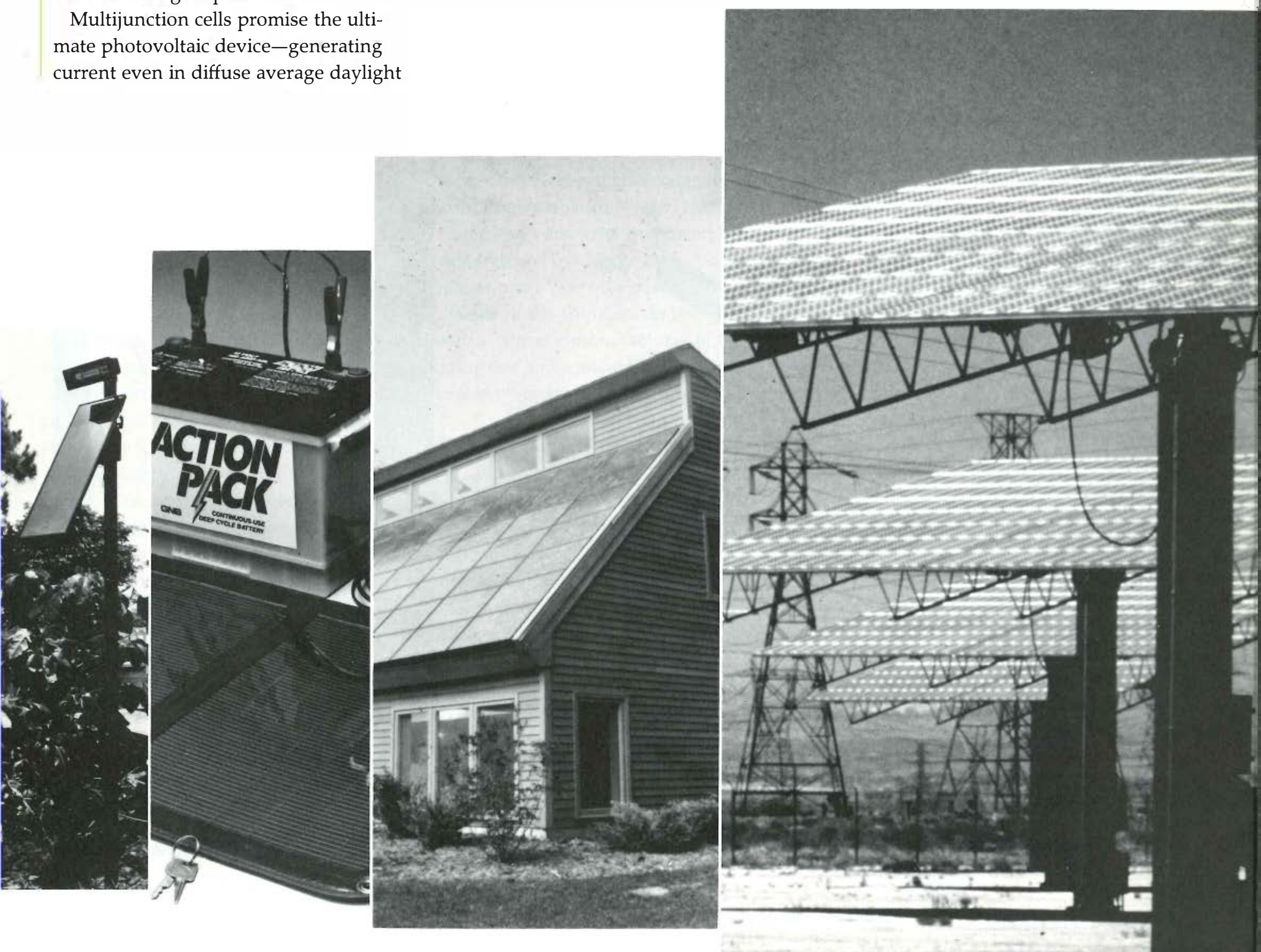
silicon (a-Si), has a practical limit of 14%—a little over half that of crystalline forms. Although experimental a-Si films have reached 12% in the laboratory, commercially available modules have a top rating of only about 6%.

To boost efficiencies to at least the 15% or so that EPRI and government researchers have long said is necessary, along with low cost, for thin-film modules to compete with conventionally generated power, developers have turned to more advanced, multijunction devices. Such cells and modules stack multiple layers of silicon alloys or other semiconductors that let some light through but are tailored to respond to specific wavelengths, thus converting more of the light spectrum.

Multijunction cells promise the ultimate photovoltaic device—generating current even in diffuse average daylight and with a range of use that extends beyond the Sunbelt. It has long been thought that if thin films could be deposited continuously over large areas at rates of several megawatts' worth a year, the cost per unit area would be minimal, bringing the installed cost of power below $2/W and opening the floodgates to widespread use.

"Judging from recent efficiency milestones achieved by the technology leaders and from key commercial activities, thin-film photovoltaics looks better than ever as a contender for cost-competitive solar electricity," says Edgar DeMeo, EPRI's program manager for solar power. "As for photovoltaics in general, its acceptance by utilities from a power plant operational point of view is a virtual certainty, based on experience to date with major field tests. Moreover, it appears that the potential bulk power market for photovoltaics through the 1990s exceeds manufacturers' current and planned production capacity by a wide margin."

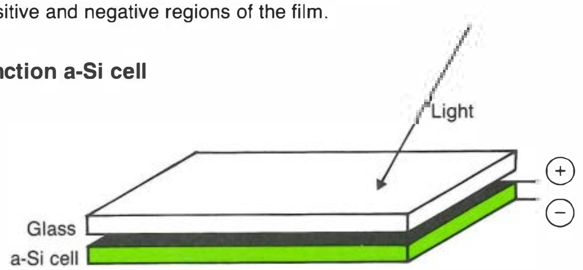
But the optimism is tempered by growing recognition that, after nearly two decades and more than $2 billion in private investment, photovoltaics is not yet a profitable industry. Without substantial new sales and market develop-



Stacking Up Thin Films: Multijunction Cells and Modules

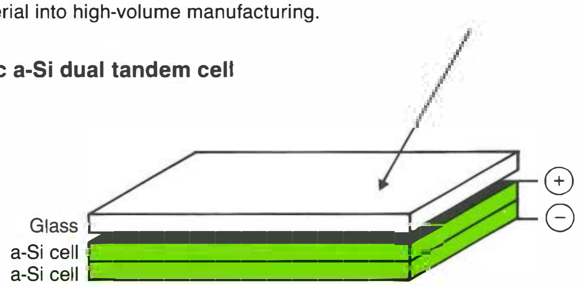
A simple thin-film PV cell consists of a layer of a-Si or other semiconductor about a micrometer thick that is vacuum-deposited on a substrate. Terminal interconnects are wired to positive and negative regions of the film.

Single-junction a-Si cell



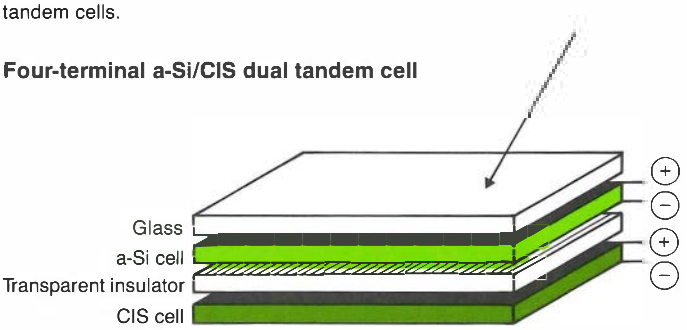
To boost sunlight-to-electricity conversion efficiency above the 15% or so necessary for economical electricity generation, manufacturers and researchers are working on multilayered cells tailored to respond to a broader spectrum of light. One approach adds a second thin-film cell of a-Si, alloyed to absorb more red light, directly beneath a translucent a-Si top cell to form a monolithic dual tandem structure. The challenges are, first, to actually produce such alloys of a-Si with high quality and, second, to scale up the material into high-volume manufacturing.

Monolithic a-Si dual tandem cell



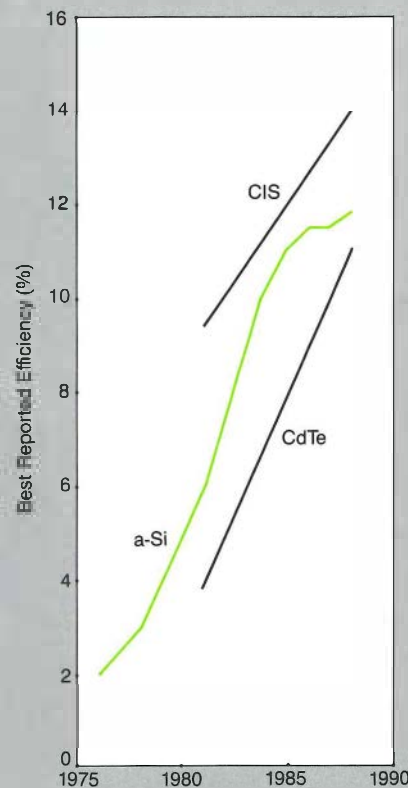
An alternative for achieving higher efficiency that is being pursued by at least one PV manufacturer is to combine two cells with separate terminal leads into a multijunction tandem device. ARCO Solar is developing a four-terminal dual tandem module of a-Si and CIS. Only a transparent, adhesive insulating film separates a translucent a-Si top cell from a bottom cell of CIS. Although the technology for such cells appears to be in hand, it also appears that they will be more expensive to manufacture than monolithic tandem cells.

Four-terminal a-Si/CIS dual tandem cell



A Material Difference in Efficiency

Significant gains have been made over the last decade in the efficiency with which thin-film solar cells of several different materials convert sunlight to electricity. In addition to amorphous (noncrystalline) silicon (a-Si)—the material from which ultrathin photovoltaic films were first developed—major progress has been achieved in the efficiency of cells made of copper indium diselenide (CIS) and cadmium telluride (CdTe), both polycrystalline materials. Although CIS and CdTe each became a focus of PV research in the late 1970s, the graph reflects only results reported in the available scientific literature.



ment soon, many investors may be nearing the end of their rope. Commercial developments in the next few years will be critical to whether the R&D momentum can be maintained and carry photovoltaics into assured, long-term economic viability.

Progress in the lab and the marketplace

Interest in thin films is accelerating worldwide. In the United States, substantial efforts are under way with both corporate and government support. In addition, a substantial government-industry program has been under way in Japan since the late 1970s, and activity in Europe has been expanding rapidly for several years in both the private and government sectors.

An important part of the U.S. R&D in thin-film photovoltaics is carried out under a cooperative government-industry research program managed by the Department of Energy's Solar Energy Research Institute (SERI). Major programs—one in amorphous silicon and others in polycrystalline materials such as copper indium diselenide and cadmium telluride—are now federally funded at about $11 million a year, with up to half again as much from the photovoltaics companies themselves.

"The continued technical progress in photovoltaics has been the most positive testimony to the success of the government-industry partnership," notes Jack Stone, director of SERI's solar electric research division. "This progress has been most evident in the amorphous silicon, polycrystalline, and high-efficiency thin-film programs. Once only laboratory curiosities, many of these technologies are now significant contributors to the worldwide market for photovoltaic products and promise to be key players in the future electric utility markets."

EPRI's R&D support in thin films complements the government-industry efforts with a program focused on basic physics and materials research at several universities. The key to the long-term future of PV may lie in such research and in finding which combination of device material, design, and efficiency can now and ultimately be manufactured at the greatest rate and the lowest cost.

But manufacturers are not waiting for the science or for the ultimate thin-film device. Thin-film modules have already been developed for niche markets and high-value applications, and developers continue to seek new markets. A look at what is now available, and what soon will be, reveals a maturing technology in transition from the laboratory to the marketplace.

Since soon after 1974, when physicist David Carlson, then at RCA Laboratories, made the first thin-film PV device from amorphous silicon, it has been considered the best hope for an inexpensive solar cell that could work effectively in moderate daylight. "In response to the energy crisis triggered by the Arab oil embargo, I was looking for a thin-film PV material that could be readily grown over large areas," recalls Carlson, now vice president and general manager of the thin-film division of Solarex, a major manufacturer of PV equipment and a subsidiary of Amoco (formerly Standard Oil of Indiana).

By the mid-1980s, several photovoltaics companies—Solarex, ARCO Solar, Energy Conversion Devices (ECD), and Chronar—had begun making and selling a-Si thin-film modules with efficiencies of 4–6% (in the first two cases as a complement to an existing line of more efficient crystalline product). Today, in corporate and university laboratories in the United States and Japan, efficiencies of single-junction cells have reached about 12%, very close to the practical limit of 14% for a-Si. ECD has made a two-terminal triple-cell stack that is 13.7% efficient, using a-Si alloyed with germanium (to better absorb red light) in the bottom layer.

But amorphous silicon and related alloys suffer from a particularly undesirable flaw for a solar cell—a tendency for conversion efficiency to degrade with exposure to sunlight. Current modules typically lose 10–15% of initial power within the first year of operation. While manufacturers simply derate their product to its stable rating and insist the phenomenon is not a problem, it nonetheless helped focus attention several years ago on alternative thin-film materials that do not lose efficiency.

Working with copper indium diselenide (CIS), an exotic polycrystalline material pioneered by Boeing Electronics for space-power applications, ARCO Solar has reported an impressive 15.6% efficiency with a small four-terminal multijunction device of stacked layers of translucent a-Si and CIS. Over 12% has been reached in a 1-ft^2 module. So far, CIS cells appear to be immune to light-induced performance degradation. ARCO Solar could begin commercial production of tandem a-Si/CIS modules this year pending field tests. Within the next few years, modules exceeding 15% efficiency are anticipated, the oil company subsidiary says.

Another polycrystalline material, cadmium telluride (CdTe), is the focus of other firms because of its potential for very low cost production by electrodeposition, spray pyrolysis, and even silkscreen printing. Ametek Applied Materials and Photon Energy, under SERI cofunding, have achieved the highest CdTe efficiencies for cells (11%) and modules (6.1%), respectively.

International oil giant British Petroleum (which inherited CdTe pioneer Monosolar's patents and technology when it bought Monosolar's buyer, Standard Oil of Ohio) reportedly will begin commercial production of CdTe modules this year. Photon Energy plans to begin manufacturing for wholesale this year. Meanwhile, Ametek Applied

Materials, a division of Ametek, a large original equipment manufacturer, is looking for partners to venture into pilot-scale production. Matsushita is also actively pursuing R&D in CdTe photovoltaics.

Both CIS and CdTe, while attractive as solar cell materials because of their potential for high efficiency, enjoy a less developed technical data and experience base than does silicon. Both involve heavy metals and several toxic compounds, raising issues for manufacturing as well as for safe operation. Proponents of CIS and CdTe counter that silane—the hydrogen-silicon gas used in making thin films of amorphous silicon—is also toxic and, moreover, explosive.

Some PV manufacturers—Mobil Solar, for example—are focusing exclusively on crystalline silicon for eventual bulk power markets. Although in some cases efficiency goals for crystalline silicon have been met, even the best high-volume modules still cost around $4/W, well above the $1/W (and roughly 15% efficiency) EPRI believes it takes for any flat-plate PV module—crystalline or thin film—to make electricity at a cost (6–8¢/kWh) that rivals conventional power.

Betting on silicon

One manufacturer that is covering nearly all the bases and pledging a long-term commitment to the business is Solarex, the holder of Carlson's seminal patents and the first U.S. commercial producer of a-Si thin-film cells. The 15-year-old firm, one of the leading PV makers today, ships several megawatts a year from half a dozen factories and counts revenues (publicly unreported) in the tens of millions of dollars, according to John Corsi, Solarex's president.

Since early 1984, Solarex has been making a-Si thin-film modules of about 5–6% efficiency that are gradually phasing into the lower end of its 2- to 64-W product line. The company has plans for a computer-integrated, state-of-the-art 10-MW/yr thin-film manufacturing plant operation. Its timing, says Corsi, "is a function of how we see the market developing and how soon we feel the market will be ready to accept large volumes of thin-film product."

Although Corsi says Solarex's semicrystalline silicon technology is "very cost-effective today for many applications" and remains "an important part of our future—our core technology for the market" in remote-power applications—the advanced thin-film factory should be capable of making product for as little as $1.30/W. That leaves $1.20/W to cover the balance-of-system (BOS) costs and still meet a target installed cost of $2.50/W, "which begins to approach the range where PV is cost-competitive with utility peak power today, around 12–15¢/kWh," says Corsi. "That's with no improvement in efficiency," he says, adding that while Solarex does not believe BOS costs today are as low as $1.20/W, that number and a $2.50/W total installed cost "are realistic, achievable goals."

Corsi thinks those numbers and the sorts of developed markets that could support production to meet those goals are two to five years away. "For the immediate future we're focusing on remote-power markets in the broadest sense. And we're also beginning to see significant activity in the decentralized, grid-interactive markets on farms and at some residences, where the economics can also favor photovoltaics," he says.

For the long term, Solarex is betting that a-Si thin films (including alloys) have the greatest potential for further cost reduction and the best chance among other thin-film materials for low cost and high efficiency. "We started a-Si in this race, and we continue to believe that's the one that's going to finish," says Corsi. "We're not ignoring other possibilities. Still, we believe there are serious obstacles inherent in these other materials that we do not see with a-Si."

Another PV manufacturer betting on a-Si is Energy Conversion Devices. The Troy, Michigan, company's founder and president, Stanford Ovshinsky, was one of the earliest proponents of a-Si as a low-cost semiconductor. After 25 years as a public company, ECD has parlayed its expertise in the material into numerous patents, licenses, and subsidiaries involving flat-panel displays, imaging systems, optical memories, electrophotographic materials, and semiautomated manufacturing of thin-film PV modules, although it has yet to turn a profit.

"We've always had the world's highest photovoltaic efficiencies in a-Si because we've had better materials," claims Ovshinsky. "We have the highest efficiency in a triple tandem cell at 13.7% and the highest in a dual tandem at 13%, and the next step will take us to 14%. I believe we can go to the 18–20% range in the relatively near term."

Subhendu Guha, ECD's vice president for photovoltaics, is more cautiously optimistic: "We could go to 15% without any material improvement, although there is a little every year. So I can see 16–17% within two years, but not 18%. For that we need another breakthrough." To get to 13.7%, ECD has alloyed a-Si with germanium in the bottom cell; a novel "profiling" technique in which the germanium content varies within the cell also contributes to current collection.

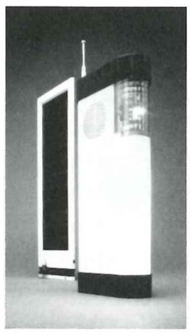
Today, in production, ECD turns out 6.6%-efficient dual tandem modules on stainless steel substrate in a proprietary continuous roll-to-roll machine. The product sells for about $4/W. ECD is looking for a partner to fund the conversion to triple tandem high-efficiency module production, which Guha projects would bring the cost down to $2/W. Meantime, to survive, the company is counting on continued sales of costlier, less-efficient modules in such high-

From Calculators to Power Modules: A Growing Product Array

Pocket calculators and watches powered by small built-in PV cells of thin-film a-Si first appeared on the consumer market in the late 1970s. Since then, thin-film photovoltaics has expanded into a diverse assortment of consumer and specialty solar products that are finding niche markets in low-power, mostly remote, mobile, or marine applications. These range from indoor appliances and outdoor lights to livestock fence chargers on the farm and battery chargers for vehicles and boats. Power modules of 20 W or more are now available from several manufacturers for any number of uses, including connection into larger arrays. For many thin-film PV producers, high-value niche markets are important stepping-stones to distributed and central station bulk power markets, where improved cost and efficiency factors are required in order to compete with conventional electricity generation.

(Photos courtesy of ARCO Solar, Chronar, Energy Conversion Devices, and Solarex)

Glider battery charger

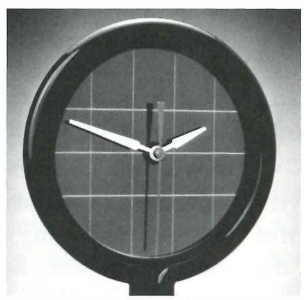


Portable radio/flashlight

Outdoor light

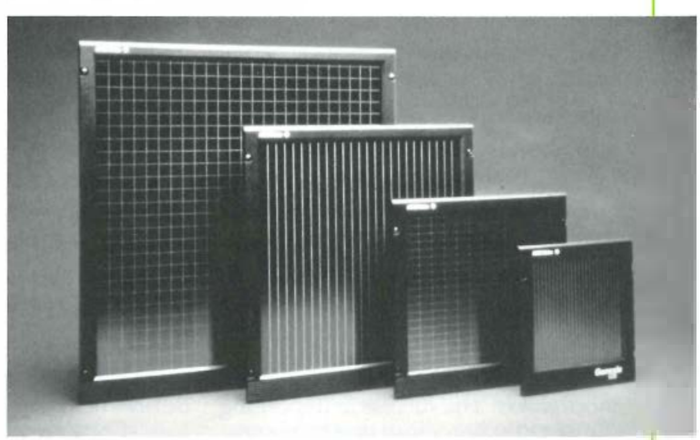
Watch

Calculator



Clock

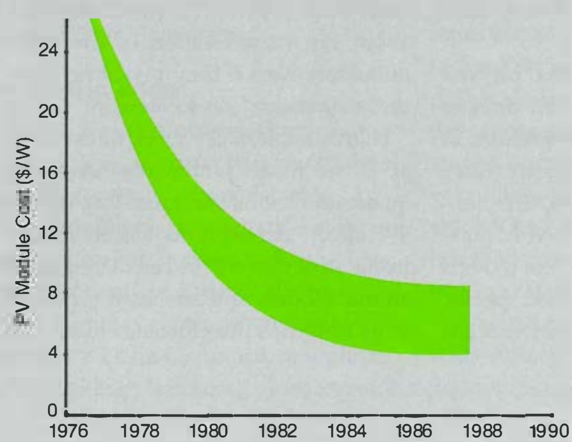
Marine battery charger



Power modules

Markets Expand as Cost Falls

New uses for photovoltaics have become economical over the years as the cost of modules has declined through production improvements and greater volume. The band of costs reflects several PV technologies, including thin films, and different levels of production. Advances in thin-film materials and manufacturing methods promise to push the lower boundary even lower in the years ahead.



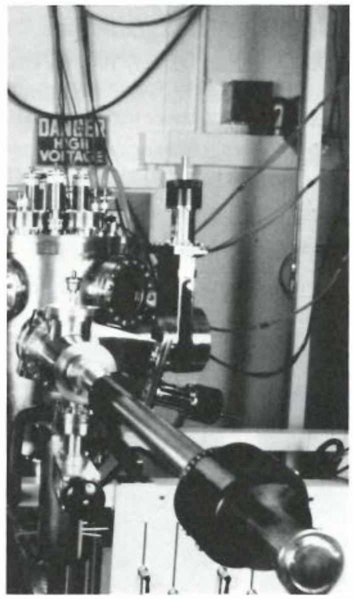
Extending the Limits of Thin Films

EPRI-funded R&D is contributing to better understanding of amorphous materials for thin-film photovoltaics in key areas at the limits of present technology. These involve high-quality amorphous silicon (a-Si) alloys tailored to absorb red light, the kinetics of amorphous thin-film deposition, the modeling of fundamental physics and device operation, and various aspects of the phenomenon of light-induced efficiency loss, known among researchers as the Staebler-Wronksi (SW) effect, after its discoverers.

Research in these areas is conducted at leading universities under a closely coordinated effort that includes review and feedback from PV industry scientists and engineers. Ongoing for some five years, EPRI's thin-film research is now funded at about $1.5 million a year, nearly a third of which comes under the Institute's exploratory research program.

EPRI's efforts in thin-film PV were initiated at the urging of a spectrum of the PV community, particularly the industrial sector. "It was recognized early on that to get the required high efficiencies, fundamental materials and device research was needed beyond a time frame typical of industrial research," explains Edgar DeMeo, solar power program manager.

In the last three years, according to Terry Peterson, project manager, "there has been remarkable progress overall. At the outset, it wasn't clear if anyone could make amorphous silicon-germanium [a-Si:Ge] of device quality. Now we are very close and are confident that we can succeed with more work." The success in depositing



low-bandgap alloys while maintaining good electronic properties has come at Princeton University, where carefully prepared and defined materials are emphasized and state-of-the-art techniques are used to minimize contamination with impurities.

At the University of Illinois, researchers are using advanced deposition techniques, including reactive magnetron sputtering, to observe and begin to control the kinetics of film growth. Insights gained from this effort could be critical to improving the uniformity and rate of large-area deposition, the keys to high-volume, low-cost manufacturing.

To better understand the physics of how amorphous thin-film devices operate, EPRI-funded researchers at Pennsylvania State University have developed generalized computer simulation models. Coupled with measured material properties, the models of various semiconductors and specific devices help improve fundamental understanding of materials and characterization experiments so that other researchers can optimize thin-film materials without actually making complete PV devices.

An expanding dimension of EPRI's thin-film work is focused on the SW problem, the decrease in photoconductivity in a-Si over time with exposure to light. Peterson notes that although sophisticated device design promises to reduce the effect, it would also impair manufacturing yield. "A more satisfactory solution awaits better understanding of the phenomenon," he adds.

On the basis of its work with a-Si: Ge, the Princeton group theorizes that the performance degradation results from intrinsic defects that are quenched into the material when the films cool after growth. The group's counterparts at the University of Illinois tentatively note a correlation between the magnitude of the SW effect and the hydrogen content of films made by reactive sputtering.

Just-begun experimental and theoretical work at Stanford University aims to develop testable predictions derived from thermodynamic properties of extensively characterized material samples. "We should get some definitive data that tell us something about the manifestation of the phenomenon even if they reveal no new understanding," says Peterson.

Highly exploratory work under way at Iowa State University involves quantum-mechanical modeling of the SW effect. Amorphous silicon's electronic structure will be calculated from atomic models and analyzed for clues to its link with the efficiency loss. □

value markets as military and remote communications. It has begun licensing its manufacturing technology to firms in other countries.

Like some others in the PV industry, Guha disagrees that 15% module efficiency is essential for PV to compete with conventional forms of bulk power generation. "We know what our cost of production is, and our calculations suggest we could bring that down to 80¢/W, fully loaded, with a plant able to manufacture 10 MW a year. If the modules were only 10% efficient, the product would be economically competitive with other energy sources," says Guha. "We have the technology to do that today." He cites estimates by Bechtel and Sandia National Laboratories that BOS costs could be as low as $1.20/W.

Also betting on a-Si, also projecting cost-competitive PV power with 10% module efficiency, and claiming BOS costs under $1/W is Utility Power Group, a small California module maker with its sights on the turnkey utility systems market. UPG's president, former ARCO Solar engineer Michael Stern, says the company initially hopes to land several utility or third-party projects in the 50–200-kW range to build a reputation and expand manufacturing.

UPG's single- and dual-junction thin-film modules, both about 6% efficient in production, will reach 10% efficiency within the next couple of years, Stern predicts. "Our analysis says that at 10% efficiency you could generate electricity for 6¢/kWh, which opens the floodgates of demand for PV systems."

Out on the edge

Of all the thin-film manufacturers committed, at least for now, to a-Si, Chronar Corp. is one about whom there are different opinions as to whether it is helping the photovoltaics industry. One of the few publicly traded PV companies, Chronar continues to make headlines with its manufacturing plants (including three overseas), consumer PV products, and the grand vision of its inimitable founder, chairman, and chief executive, Zoltan Kiss.

The Hungarian-born physicist-entrepreneur, who pioneered liquid-crystal displays in the late 1960s, today heads a 13-year-old company that has not yet begun to turn a profit. Years of losses in the millions were sustained in becoming the largest producer of a-Si thin-film modules. Kiss claims that the direct cost of manufacturing is now 75¢/W (excluding plant depreciation) and that it will soon drop to 50¢/W, bringing installed system cost within $2.50/W and generating electricity for 11–12¢/kWh.

"From day one our goal has been to make the lowest-cost-per-watt device," says Kiss. "To do that we have developed a manufacturing process that takes an ordinary piece of float glass through an integrated operation to come out with a finished product at the other end."

More than half today's 75¢/W direct cost is for labor, Kiss concedes, a component he expects to nearly eliminate in a fully automated 10-MW/yr plant Chronar and several partners are planning in northern California by 1990. To show off the product while taking advantage of attractive utility rates for supplemental peak electricity, Chronar and an alternative energy developer are seeking investors for a $125 million, 50-MW thin-film generating station in southern California by 1992.

Such a plant would be over seven times larger than any PV power facility today. "We are pushing this 50-MW power station not because that's where the profits are but because that's the way to open up the market, the way to get utilities to believe this is really doable," Kiss explains, adding that, at an installed cost of $2.50/W, "we won't be making much profit, if any."

If such a power plant is financed and built—which Chronar itself says is dependent on investor tax benefits—it will use thin-film modules that will be only about 6% efficient, slightly better than the 4–5%-efficient panels that the Lawrenceville, New Jersey-based company makes today. (Chronar is also working on more efficient a-Si alloys and multijunction cells.) But it is because of numbers such as these that Kiss's insistence on the eminent arrival of utility-competitive solar electricity—7¢/kWh by 1992, he says—is greeted skeptically in many quarters.

Chronar has gotten a lot of attention for its success with a growing line of PV consumer products, particularly a low-intensity solar/battery-powered garden light that requires no wiring. Revenues have been in the double-digit millions for three years. Despite anticipation that it might finally break out of red ink last year, Chronar now expects to break even at best.

Several factors taken together—module failures at an Alabama demonstration, the low efficiency of the typical Chronar product today, and the sorts of claims that a growing, publicly held company seems compelled sometimes to make—give many in the PV and energy research communities cause for concern. They worry that if Chronar fails by overextending itself and overselling its technology, it could dim much of the rest of the industry's prospects.

On the other hand, Chronar has convinced some pretty serious players—Bechtel and Pacific Gas and Electric among them—that it can deliver and is in the business to stay. The California manufacturing plant will be a joint venture with PG&E Enterprises (PG&EE, an unregulated subsidiary) and a unit of the Sheet Metal Workers' pension fund. PG&EE and Bechtel are providing project management assistance as well as financial support. Moreover, PG&EE has taken a $1.8 million stake in Chronar stock, joining the Sheet Metal Workers' fund, the National Electrical Contractors' pension fund, and other large equity investors.

Kiss can be a compelling evangelist when he talks of the billion-dollar market, ripe for today's photovoltaics, in battery-powered gear using electricity effectively costing 75¢ to $1/kWh. With a new line of industrial products including billboard lights and power panels for irrigation pumps, Chronar is already going after the even bigger market in the 50–75¢/kWh range. But the "really enormous" market is in the 15–40¢/kWh range, says Kiss, "where there are literally tens of gigawatts of targets," now powered by diesel generators, around the world. "For all of this, amorphous silicon as it is today, not how it may be sometime, as it is today, at 50¢/W direct manufacturing cost, is more than cost-competitive."

Chronar's investors are betting Kiss is right. A lot of competitors and others with an interest in photovoltaics are hoping Kiss isn't proved wrong.

Beyond silicon

Although several thin-film PV makers are sticking with a-Si and its alloys for now, all of them stress they are also keeping an eye on other materials with the potential for low cost and higher efficiencies. Recent performance milestones with CIS and CdTe are enough to prevent any manufacturer not involved with those materials from feeling smug about silicon, with which there is deeper understanding and manufacturing familiarity.

"CIS is the material that has made the most headlines lately, and ARCO Solar is in the efficiency forefront with CIS, having reached over 14% with a 4-cm² cell and over 11% with a 1-ft² CIS-only module," says Terry Peterson, EPRI project manager for thin-film photovoltaics. Peterson notes that present CIS cells "are not very thin films as the technology is practiced today," being 2–5 micrometers thick compared with typical a-Si films of less than 1 micrometer.

One of the earliest manufacturers to commercialize a-Si thin films, ARCO Solar has led the PV industry on numerous technological fronts. Not the least of these are several megawatt-scale power station demonstrations of crystalline Si PV in California that have confirmed very low operating and maintenance costs and PV's good power match with utility peak demand (at least in the Golden State).

Despite its leadership in thin-film technology and a backlog of orders for its still strong-selling crystalline Si products, ARCO Solar may be in for major changes, observers say privately. Several researchers were laid off in a consolidation (trimming, say some) of R&D operations last fall, consistent with talk for some time that the U.S. oil giant is considering shedding its solar subsidiary. James Caldwell, ARCO Solar's longtime president and CEO, resigned late last year and is seeking partners to buy the company.

Caldwell says that the possible sale of ARCO Solar would be only another example of a major oil company with solar energy interests acquired in the 1970s having lost patience waiting for a return on its investment (although several oil firms apparently remain strongly committed).

"There's more private investment capital for photovoltaics now than a year ago, but it's coming from new and different sources than the oil companies, who increasingly seem to want to stick to the oil business," Caldwell said early this year. He called the shift in equity funding "a measure of the maturing of the PV industry."

Charles Gay, a former research manager and senior vice president who is the new president of ARCO Solar, says the company plans to commercialize CIS technology. The timing will depend on the outcome of field performance testing, including evaluations that began at SERI last November. "We have to be completely confident of the durability of large-area CIS circuits, from packaging to interconnects, in addition to the basic material durability," adds Gay. For the near term, meanwhile, "there will be a lot more thin-film silicon to come from ARCO. Last year we finished expansion of the manufacturing line to 7 MW a year of capacity. We still see a bright future for silicon."

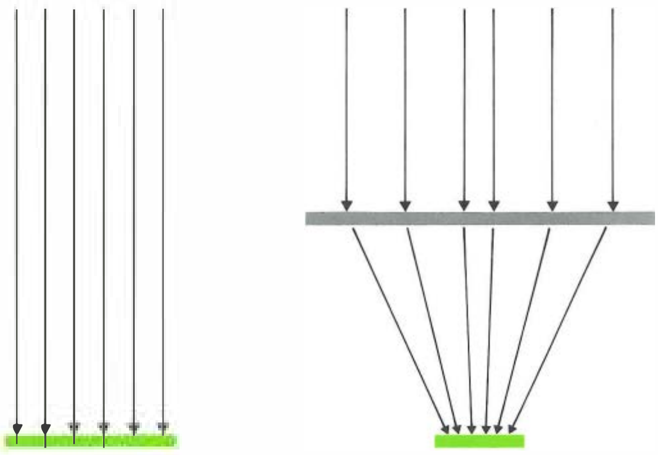
Says Vijay Kapur, a former ARCO Solar research director and now president of International Solar Electric Technologies (ISET), "ARCO Solar has certainly had a leadership role in CIS development, and I hope they stay around. Frankly, it helps us." ISET, a small southern California PV concern, is the only other U.S. firm openly pursuing CIS for nonspace application. It conducts government-funded R&D on electroplating and other processes for CIS, CdTe, and cadmium zinc telluride (a related material for tandem cells). Kapur says ISET has proprietary processes for making CIS and CdTe solar cells and is looking for backers and the opportunity to get into pilot production.

With sufficient funding, ISET could gear up to making 10%-efficient modules at a cost of $1.50/W within three to four years. To get module efficiencies over 15%, Kapur thinks a tandem device with a cadmium zinc telluride cell overlying a CIS cell looks attractive.

Polycrystalline thin-film materials such as CIS and CdTe are attracting attention not only because of their good photovoltaic properties but also because they lend themselves to electroplating, a widely used, very low capital cost industrial process. The head of the Ametek unit pursuing CdTe says that feature makes setting up small-scale local thin-film factories in less-developed countries attractive as a business sideline or alternative to domestic manufacturing.

"Groups like the World Bank and USAID are funding PV applications in the Third World right now that are extremely cost-effective compared with

Another PV Approach



Thin films are one of several photovoltaic technologies that show promise for prospective bulk power applications. Another approach is to use small but very efficient cells illuminated with highly focused sunlight. Arrays of such cells equipped with lenses track the sun through daily cycles to maintain the focused light at several hundred times normal intensity.

EPRI sponsors a substantial effort in high-concentration photovoltaics, which was begun more than a decade ago and is cofunded by a number of utilities. Recent activities are directed at verifying technical performance and identifying industrial partners for further development (see the research update on p. 46 of this issue).

The different PV technologies are expected to pursue separate paths as they mature toward commercial applications on a large scale. Although concentrator cells have achieved the high conversion efficiencies (26–28%) that are necessary—along with acceptable reliability and cost—for competitive bulk power generation, systems using such cells do not appear to be well suited for most of the near-term markets that have been identified. Flat-plate systems, in contrast, are relatively simple and lend themselves to small or remote but high-value commercial applications. Such niche markets are important to PV manufacturers because they can support continuing technical development toward larger, bulk power applications.

Concentrating systems, on the other hand, are likely to have few business development stepping-stone markets on their way to utility power applications. Lacking the incentive and fuel of revenue from near-term commercial products, the industrial base in concentrating systems is much smaller than that involved with thin-film and other flat-plate PV alternatives. Development of this industrial base will be as important as technological progress if concentrator systems are to succeed at the utility scale. □

diesel generators or no electricity at all, and the PV manufacturers all say they can supply the technology, so why isn't the use of PV in developing countries more widespread?" asks Peter Meyers, director of Ametek Applied Materials, Harleysville, Pennsylvania. "It's because there is no local infrastructure for manufacturing, distribution, sales, service—anything.

"I think we could fill a need by setting up manufacturing facilities on the order of 500-kW/yr capacity in remote areas of many countries. Plants that size could manufacture CdTe modules for about $3/W—that's something the a-Si people can't do," says Meyers. CdTe electrodeposition is low-tech and inherently safe, and it requires little training for production workers, he adds. Meyers discounts the environmental hazard imputed to cadmium, saying the amounts implied are small and the challenge is limited to reclaiming nonvolatile process liquids.

In keeping with the parent company's tradition as an original equipment manufacturer, Ametek Applied Materials could someday become a wholesale supplier of CdTe modules to retail manufacturers and eventually would like to break into the utility systems market, says Meyers. For now, the company makes 3-by-6-inch submodules that are typically about 6%, and sometimes as much as 9%, efficient. Like CIS, CdTe appears to suffer no efficiency loss after prolonged light exposure.

Meanwhile, two firms at the extremes of size and resources plan to begin commercial production of 8%-efficient CdTe photovoltaics this year. Oil giant British Petroleum reportedly will begin selling modules, though details of its market strategy are not known. And tiny Photon Energy of El Paso, Texas, headed by electronics veteran John Jordan, plans megawatt-scale production of 1-ft^2 modules for sale to manufacturers of PV communications and remote power equipment. Jordan says

Photon Energy could shift to making 4-ft² modules by year-end.

Utilities put thin films to the test

Sensing the advent of a technology that could bring major change in several dimensions to an increasingly changing electricity supply business, more utilities than ever are getting familiar with photovoltaics. Thin-film technologies account for a growing fraction of that utility involvement, ranging from small-scale cooperative test programs with PV makers to manufacturing joint ventures to, in PG&E's case, an equity position in a PV company.

Among utilities with grid-connected thin-film arrays (all a-Si) are Florida Power Corp., with 15 kW of ARCO Solar modules; Philadelphia Electric, with 8 kW of modules installed by Solarex at the Pottstown-Limerick, Pennsylvania, airport; Detroit Edison, with 4 kW of modules on test from ECD's Sovonics subsidiary; and Wisconsin Power & Light, with 1.8 kW in Madison from the same supplier.

The largest thin-film generating station at the moment was installed in 1986 as a 75-kW field connected to Alabama Power's grid near Birmingham. The field's rating now is more like 55 kW because of some module failures, the result of short-circuiting due to poor cell construction, according to Chronar's Kiss. Near the generating site is a Chronar a-Si manufacturing plant that is a joint venture with a subsidiary of Alabama Power's parent, the Southern Company.

Without question, the utility most deeply and openly associated with photovoltaics, including thin films, is PG&E. The San Francisco–based company broadly views PV as one of several technologies that pose important new business opportunities as competition increases and regulatory barriers fall in the traditional utility industry. In addition to its stake in Chronar and the

Thin Films on the Power Grid

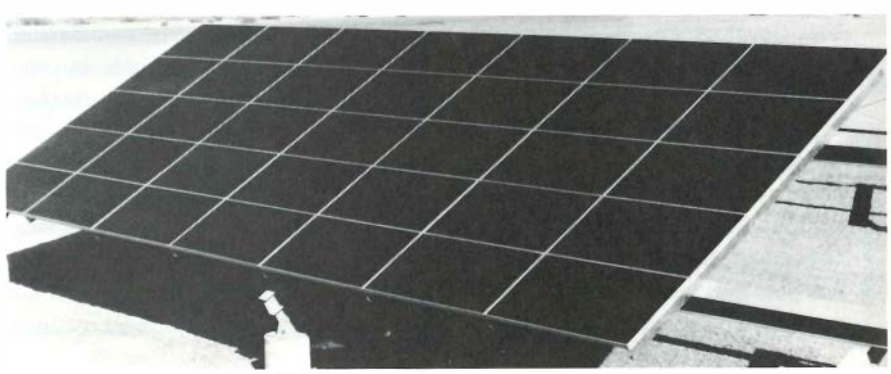
Some half a dozen utilities now have thin-film PV modules connected to their distribution systems as part of small-scale test and demonstration projects. Most are only a few kilowatts, but even larger generating stations using thin films are on the drawing boards in some areas. Many utilities are seeking early experience and familiarity with a technology that could eventually play a significant role in their own electricity supply and that of their customers.

Detroit Edison's 4 kW of ECD Sovonics modules

Philadelphia Electric's 8 kW of Solarex modules

Alabama Power's 55-kW field of Chronar modules

Florida Power Corp.'s 15 kW of ARCO Solar modules



ECD Sovonics modules at Pacific Gas and Electric's PVUSA project planned joint-venture thin-film manufacturing plant, PG&E buys the output and monitors the performance of a 5-MW crystalline Si generating station owned by ARCO Solar. For a number of years, PG&E also has tested nearly all PV manufacturers' modules and arrays at its San Ramon technology center.

Carl Weinberg, the utility's manager of R&D, says PG&E is exploring the possibilities for involvement with photovoltaics in many markets, on many levels. These range from hybrid PV and diesel, hydro, or wind mini-utilities for remote islands and the like in the international market, to domestic utility "service without the wire" applications for remote homes and highway signs, to—eventually—small and large utility-owned systems, both distributed and central station.

"There isn't a single PV system or technology that is best for all those markets," says Weinberg. "The applications are highly differentiated. In low-power consumer and commercial markets, efficiency is less important than cost and there is a market for the low-cost amorphous silicon product.

"For many remote applications, efficiency and reliability are the driver, and we think crystalline silicon will continue to be used for many of those. For the U.S. utility grid-connected market, however, our feeling is that efficiency may be less important than system costs and reliability. Typically, people have equated low system cost with high efficiency, but we're seeing some clever approaches to system costs and we think the market can work to bring them down," adds Weinberg.

An example of that—and the PG&E activity currently generating the most talk among PV manufacturers—is PVUSA (Photovoltaics for Utility-Scale Applications), an eventual 3.5-MW, $40 million demonstration of systems from various suppliers for which the utility has obtained major federal and some state cofunding. EPRI is also a cosponsor of PVUSA, funding performance assessment and reporting activities. Launched in 1986, PVUSA is intended to spur system-scale tests of technology that would not otherwise be in production and to foster innovation in lowering balance-of-system costs.

In the first phase of PVUSA, the installation of 20-kW arrays of modules (including crystalline and amorphous silicon flat-plate and concentrating technologies) from five manufacturers near Davis, California, is to be completed by midyear. Subsequent rounds of 200–400-kW increments of complete turnkey systems engineered for high reliability and low system costs would follow, beginning in the early 1990s.

While most of the major PV manufacturers will participate or want to participate in PVUSA, some privately express concern either that the project diverts scarce federal appropriations from still-needed basic research or, at the other end of the spectrum, that PVUSA's extended time frame and initially small scale send a message that PV remains at the test stage. Still, it has given some manufacturers a reason to keep production lines operating, and future rounds serve as targets on which to bid and set sights.

"We think that without some kind of interim project like PVUSA, the development toward commercial utility applications might disappear," says Weinberg. "If utilities are ever going to go after PV, there must be a relatively large operation owned and operated by a utility so everybody can see it and study it and understand where all the costs are and how to tweak them.

"Utilities have really got to understand and be comfortable with PV, because it doesn't fit well with traditional utility planning methods and models, although we believe it potentially can play a significant role in utility service in the future."

A precarious place for PV

Now may be the best of times and the worst of times for photovoltaics. The technology in general has made major progress over the last decade and a half toward the levels of performance and cost believed necessary to carve a permanent place as a true electricity supply option and not just the stuff of consumer products and special remote gear. So far, it has successfully weathered the low mark of depressed oil prices to which its fate was formerly believed to be inextricably tied. Recent growth rates in industry sales and revenues have been impressive, although the same can not yet be said of individual corporate earnings. "There is a solid basis for optimism that photovoltaics is catching on," notes EPRI's Peterson.

But many in the PV community worry that, without a substantial brightening of the current business outlook, without some breakthrough in new products and applications or in the fundamental technology, the momentum and the lead of U.S. manufacturers are threatened. "Most of the companies feel we're getting very close to put-up-or-shut-up time," says DeMeo. "The U.S. photovoltaic effort is in danger of being uncompetitive because the American PV community is not well coordinated.

"I sense a concern that if the PV community doesn't pull itself together soon in a coordinated, coherent assault on development and deployment of the technology in a way that optimizes the use of available resources, the U.S. industry isn't going to make it in the global market. Others—Japanese and European firms—may," adds DeMeo. "But we in the United States do have the needed resources, and it's still a wide-open race. And the potential markets are so large there is room for a number of winners."

This article was written by Taylor Moore. Technical background information was provided by Edgar DeMeo and Terry Peterson, Generation and Storage Division.

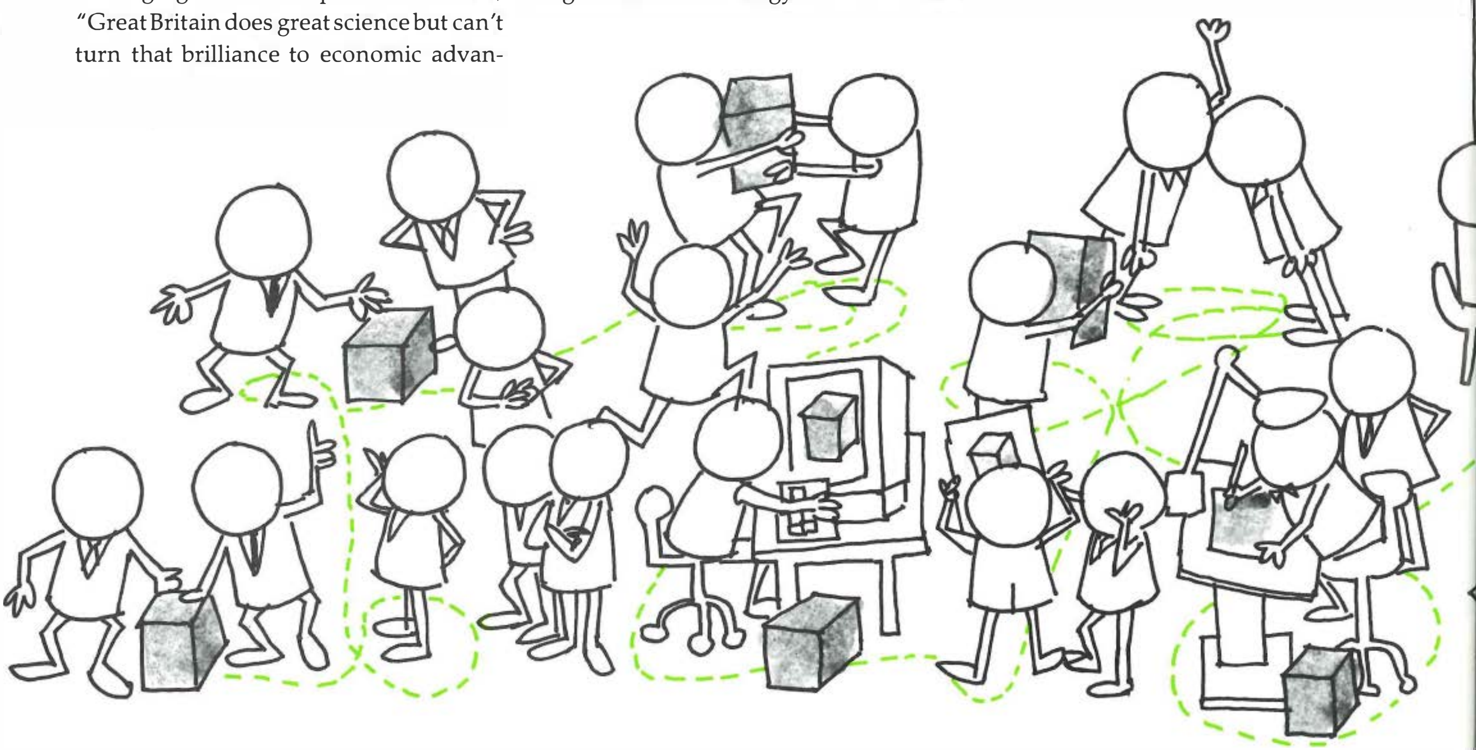
"The critical issue in technology innovation is no longer the ability to do good science or even to devise new products, but to win out in the subsequent fierce international marketplace," asserted Nathan Rosenberg, economics professor at Stanford University and the kickoff speaker at the EPRI Advisory Council Seminar on Technology Innovation.

In Rosenberg's mind, the key to the new economic battle lies on the development side, the "D" of R&D—the continuing stream of small improvements in engineering, product design, and production that win no Nobel prizes and get only limited recognition from the patent office, but that can and do prove decisive to market success.

Bringing home his point he added, "Great Britain does great science but can't turn that brilliance to economic advantage. And we in the U.S. are having a similar problem. The accumulation of evidence is that the Japanese—and those now emulating their approach to technology innovation—give higher priority and incentives to these downstream development activities; and increasingly these downstream efforts more than offset the upstream advantages of the West."

One of the problems the United States is having is that technology itself has become a highly portable commodity around the world. New ideas, new science, and the first rough-hewn products are almost immediately available everywhere for inspection, emulation, and improvement. The head start that once tilted commercial advantage toward the originators of technology has been all but eliminated by modern information and transportation systems, throwing the weight of advantage now toward those that commit to the long, expensive haul of product development and commercialization.

"What we have seen in the postwar era is the emergence of new styles of technology innovation that are quite different from our own pioneering style—styles that can produce stunning results," said Roland Schmitt, president of Rensselaer Polytechnic Institute and former head of GE Laboratories. "Transistors, integrated circuits, computers, fiber optics, magnetic resonance imaging, VCRs, color television: these are among the seminal advances developed in the West and first



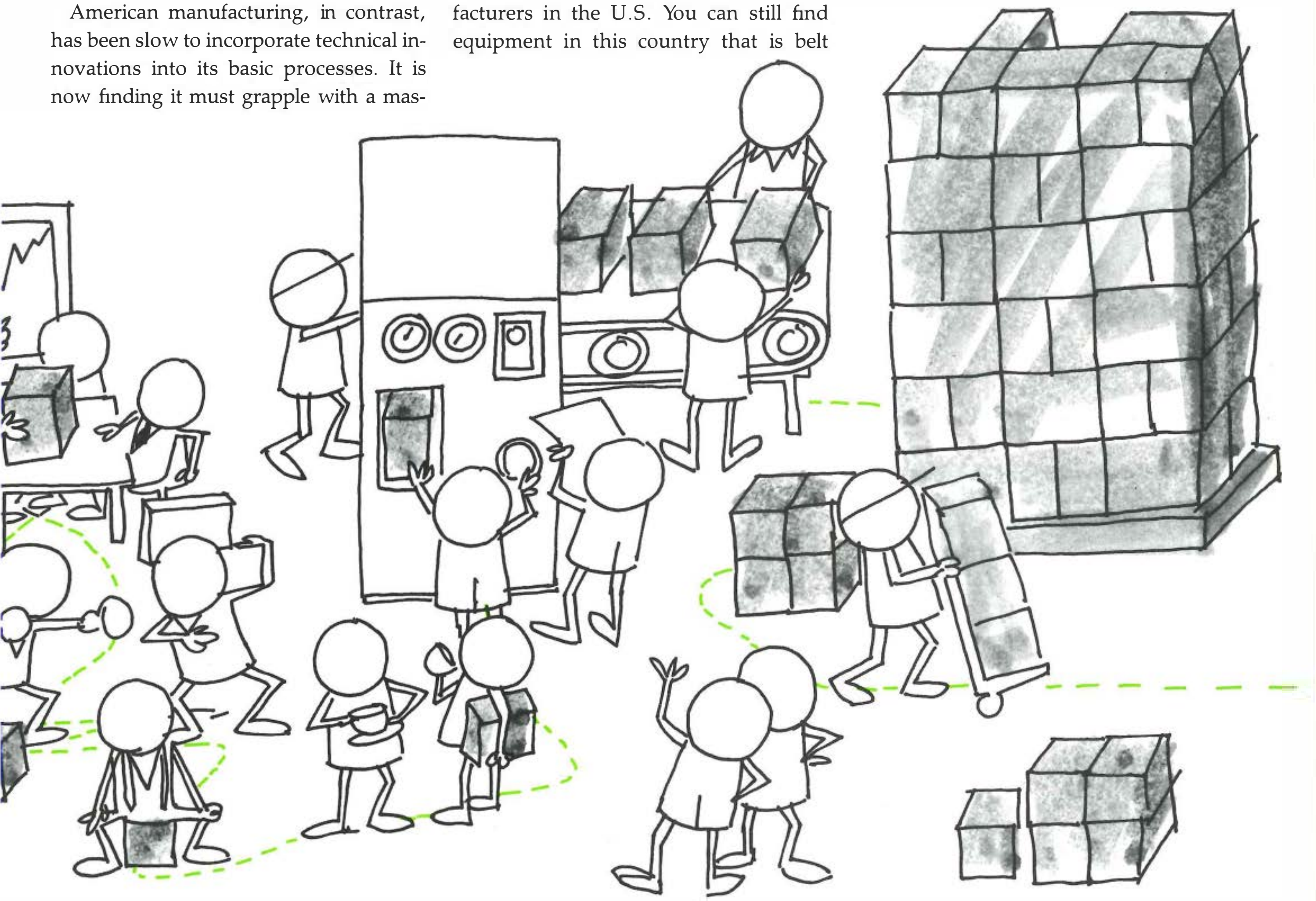
by Brent Barker

INNOVATION AND INDUSTRIAL DEVELOPMENT

embodied in new products in the West, but in which Japan and other nations have subsequently gained strong and sometimes dominant positions. Never, it is important to realize, has Japan introduced into a market the first new product based on a significant new technical breakthrough. It has always built on frontier technologies developed elsewhere, improving them bit by bit. The real strength of Japan lies on the manufacturing floor."

American manufacturing, in contrast, has been slow to incorporate technical innovations into its basic processes. It is now finding it must grapple with a massive problem of technology transfer to boost productivity and remain competitive in the global markets. When Tom Byrer, senior vice president of Battelle, Columbus and director of the EPRI-sponsored Center for Materials Fabrication, first went into the field to spur industrial use of advanced electrotechnologies on behalf of electric utilities, he was shocked to find that "innovation is just not in the vocabulary of the nearly 250,000 small and medium-sized manufacturers in the U.S. You can still find equipment in this country that is belt driven. These companies want and need help, but the technology transfer mechanisms just don't exist. The first thing they tell me is, 'Don't invent anything else, just bring in what's already out there.'"

Byrer's list of technologies waiting to be used by American industry is long and impressive, the kinds of "smart," high-



If America is a nation of innovators, why are we losing our edge in global business competition? Discussion at EPRI's latest Advisory Council seminar suggests that it's not the initial inspiration but an innovative development process—including a willingness to invest in the future—that makes the difference in the marketplace.

efficiency, precisely controlled technologies—such as plasma cutting tools—that can boost productivity to the best levels in the world. So why aren't these technologies being snatched up? Why is American industry seemingly so moribund in some areas, yet so vital in others? Lack of awareness of new and rapidly advancing technology is one reason. The difficulty of adapting and refining these tools to a unique manufacturing operation is another. But there are other factors, much deeper and farther reaching, at work in this country.

Great barriers to technology innovation

Byrer, Schmitt, and Rosenberg were among the seven speakers whose remarks opened and catalyzed two days of roundtable discussion among the members of EPRI's Advisory Council and Board of Directors and their guests, representing leaders from academia, industry, and government. Their observations and insights about the state of technology innovation in America swept the landscape—from incentives and disincentives in the American economy, to management of innovation in industry, to examples of quickening innovation in the electric utilities. But time and again the foil of comparison was directed toward Japan and its stunning success in fostering and managing technology innovation.

At the heart of the matter, we have the contrast of two countries, Japan and the United States, one epitomizing a saving economy, the other a consuming economy. National savings in Japan, for reasons of both culture and government policy, currently exceed 18% of GNP. For Germany the figure is around 11%, but in the United States net national savings fell to a historical (nondepression) low of 1.9% in 1987. The collapse in U.S. savings in the last decade was portrayed as a root-cause barrier to innovation, one that has cascaded throughout the entire American economy.

"The fundamental problem in this country," said George Hatsopoulos, chairman of the board of Thermo Electron Corporation and chairman of the Boston Federal Reserve Board, "is our extremely low (and falling) national savings rate. For 15 years U.S. productivity and living standards have stagnated, largely as a result of this chronic unwillingness to make sufficient provision for the future. The consequences of that stagnation have been masked in the 1980s by a consumption boom fueled by budget deficits and massive borrowing from abroad."

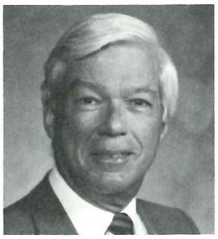
Hatsopoulos's point is that our low savings rate has shrunk the pool of capital available for investment, in turn driving up the cost of capital in the United States to the point where it has curtailed investment in the very productivity-enhancing technologies we need for global competitiveness. The basic savings problem has been compounded by two substantial drains on savings, competition for funds to feed the federal deficit, which now manages to soak up over half of our private savings, and our cultural preference for diverting savings into residential housing.

"The Japanese—and those now emulating their approach to technology innovation—give higher priority and incentives to downstream development activities; and increasingly these downstream efforts more than offset the upstream advantages of the West."

Rosenberg

The result of this squeeze on capital is that "the cost of capital is nearly two and one-half times higher here than in Japan," said Hatsopoulos. "Given this disparity, the investment of the two countries has been about right: over the last 10 years, Japan has invested heavily in technology that improves productivity—about twice as much per employee as the U.S. in the manufacturing areas." Better equipped, we would expect Japan to gain in any relative measure of industrial productivity, and indeed that has been the case. Between 1970 and 1986, productivity growth in manufacturing has averaged 6.0% per year in Japan versus 2.9% per year in the United States. "National productivity growth correlates quite closely to the capital/labor ratio for each of the advanced industrial nations. Thus Japan has been near the top; the United States, near the bottom."

But the problem has still a broader dimension. Hatsopoulos went on to say that the full extent of the American investment dilemma can only be understood by looking beyond the tangible investments in plant and equipment recorded in the national accounts to the more elusive notion of "invisible capital," which tends to be more broadly tied to business entry strategies and planning horizons. Invisible capital would include many things now viewed as expenses that help companies to initiate, build, and establish expertise, new products, market share, and a commercial infrastructure. R&D is a part of invisible capital. So is adapting or readapting a product to the tastes of the market, or establishing a dealership service network. "It is not widely appreciated," Hatsopoulos said, "that investment in these invisible assets also depends on the cost of capital, as does, more generally, the entire planning horizon adopted by business." In a nutshell, the higher the cost of capital, the shorter the business horizon for planning and decision making.



"Innovation is just not in the vocabulary of the nearly 250,000 small and medium-sized manufacturers in the U.S. These companies want and need help, but the technology transfer mechanisms just don't exist."

Byrer

American business management is often chided these days for its short-term, bottom-line myopia. In fact, the business and financial communities are often viewed as hobbling American competitiveness with their failure to think and commit to the long term. But Hatsopoulos believes they are not responding inappropriately to the current economic signals welling up from our too-small pool of savings. "Managers spend money now to make money in the future. Based on the cost of funds, Japanese manufacturing discounts future earnings at a rate of 1.5% per year (real, after-tax dollars). In the United States, the comparable discount rate for manufacturing is 6%. What this means is that the guy in Japan can wait, say, 12 years to make the same profit on the same investment as the guy here needs to make in 3 years. The low cost of funds in Japan means their capital can be much more patient, and in a strategic sense they can think and plan long term."

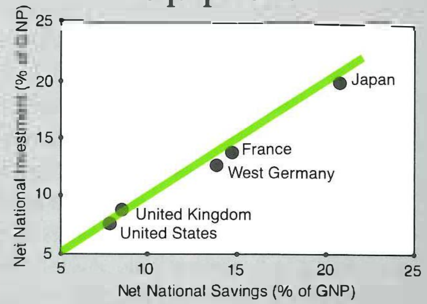
On this basis alone, no U.S. company could do what Honda Motors did. It set out in 1964 to make a profit in 1979 by developing automobiles for the U.S. market. Its invisible capital investments included building up dealerships, trying to understand the U.S. market, and a willingness to let its return on investment drop more than half and stay that way for 15 years. As Hatsopoulos pointed out, "By the mid-1980s, the investment had begun to pay off: Honda became a $20 billion company (up from $400 million in 1965), and its earnings rate rebounded to its historical level of 8.5% return on assets."

Time and again the seminar participants returned to the issue of America's short-term mentality and the crippling effect it has on technology innovation and long-term economic growth. At times the room bristled with both frustration and controlled anger. "The quarter-to-quarter earnings orientation of the financial markets, combined with the mergers we're seeing, is bad for technology innovation," said Schmitt. "Raiders are discounting the future more than rational economics say they should."

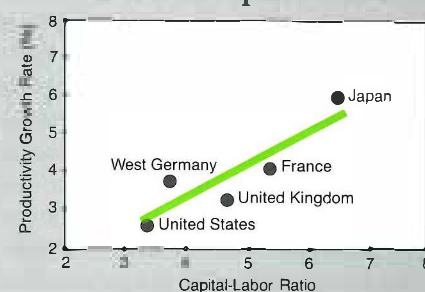
"But look," said Hatsopoulos, "the behavior of firms is ultimately conditioned by the cost of capital they face." And Judy Warrick, a former Morgan Stanley utilities industry specialist and now president of Green Lane Enterprises, added the perspective of Wall Street: "The very people bashing Wall Street are from corporate America. They are the major suppliers of pension funds—and they insist on having the very best quarterly performance, if not monthly performance. This is a circular problem. The very people who demand the performance are not happy when it comes home to roost."

The list of barriers to technology innovation cited by the participants in two days of discussion was lengthy. Perhaps none was as fundamental as the savings rate problem, but the cumulative impact of so many secondary barriers was sobering. They ranged from the dominance of defense projects in U.S. R&D (70% of

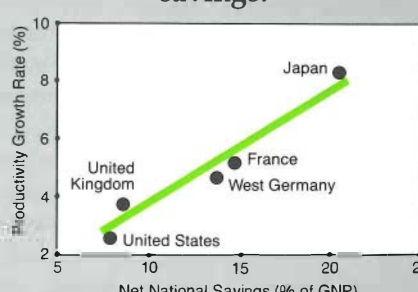
Savings provide the basic pool of funds for investment in capital equipment.



Manufacturing workers that are better equipped become more productive.



Therefore, manufacturing productivity and global competitiveness are directly linked to national savings.



Sources: Organization of Economic Cooperation and Development; U.S. Departments of Labor and Commerce.

federal R&D), to corporate policies, to the targeted industrial strategies of other nations, to the adversarial climate between U.S. industry and government. And just about everyone came in for a little bashing. Academia, for its disconnection from (and disregard for) downstream innovation. Industrial R&D and national labs, for practicing "chuckwagon technology"—cook it up, dish it out, and yell "come and get it." The technical community, for focusing its results on the wrong audience—namely, its peers. And even corporate marketing departments, for misreading the marketplace.

One common thread among these various concerns was the sense of disconnection in American practices, the failure of American industry to find and forge a smooth-flowing continuum of technical innovation from conception to commercial reality. Too many handoffs. Too much analytical detachment.

Roland Schmitt thinks this problem is epitomized in American efforts toward marketing. "The reason the Japanese can stay in touch with markets is that they don't have marketing organizations. Just look at Hitachi and Toshiba—you won't find a marketing entity in their corporate organizational structure. Here, we pile up mountains of studies on markets, but the Japanese are actually out there with their customers. They worry a lot less about foreseeing the market than listening to the market."

He cited the example of Fanuc, a Japanese firm that has captured 70% of the world market in automation controls for machine tools. "For $1 billion in sales, they have only 1000 production workers; and this ratio ($1 million per worker) is about 10 times better than the best U.S. companies. The reason is that their sales people are out there walking the factory floors of their customers, sending back weekly reports on what is wrong with their products. They are very tightly linked to their customers."

So what is the United States to do about all this? The participants spent a great deal of time exploring ways to strengthen technology innovation in America. Most agreed that the problem needs to be attacked at its most fundamental levels, namely by easing America away from its profligate patterns of consumption and, simultaneously, finding better ways to manage the innovation process in industry—ways that unify the various strengths of the U.S. "upstream" processes with those exemplified by the Japanese in the "downstream" processes.

Bursting the consumption bubble

American industrial productivity can't take off without sufficiently "patient" and plentiful capital. This means controlling consumption and plowing new savings into capital formation. Capital will allow industry to stretch out its investment horizon and to quickly embody the latest innovations in new equipment.

"The solution for our economy is to get on with national savings," said George Hatsopoulos. "The first problem is to reduce the federal deficit; the second is to increase private savings. Once you get that wheel in motion, you can afford to change the tax code to reward savings rather than consumption—a value-added tax (taxing goods, not income) would be ideal."

"The reason the Japanese can stay in touch with markets is that they don't have marketing organizations. Here, we pile up mountains of studies on markets, but the Japanese are actually out there with their customers. They worry a lot less about foreseeing the market than listening to the market."

Schmitt

No one disputed the wisdom of this approach, just the likelihood. "I'm not very optimistic about changing our consumption patterns," said Nathan Rosenberg. "Our political process makes it very difficult to curtail these habits. Government policy in the 1970s and 1980s has been a disincentive to savings. The deficit itself is a massive form of dissavings, swallowing up nearly all our capital. How fast can we turn around?

"This is probably the major public policy issue of our times," asserted Stanley Hulett, member of the California Public Utilities Commission. "The only way we are going to rebalance our economy is to put a brake on consumption, and I don't see the political courage out there to do it—to put, say, a high differential interest rate on consumer goods to force people to save."

Someone pointed out that at one time (1978) Japanese consumer interest rates were allowed to reach 105% as a means of controlling consumption—including home ownership—and suggested that it would be political suicide to consider rates at even the 35–40% level in this country.

Hatsopoulos cautioned against extreme measures, suggesting that braking too fast was not only politically unpalatable, but likely to throw the United States into a severe recession. "We just need to slow down consumption a bit—to limit the growth in consumption to about 1% below the growth in GNP between now and 2000 in order to give us the savings to revitalize our nation."

As the discussion wore on, it seemed to come down to a question of whether politics and culture could change. The new administration offered hope to many that somehow we would find the courage

Innovation on the Inside: Georgia Power and New England Electric

When you ask me about innovation in our company," said Bill Dahlberg, president of Georgia Power, "the first thing that comes to mind are the two young engineers who hooked up an $800 Radio Shack computer to one of our oldest facilities, the Jack McDonough plant, and succeeded in reducing the heat rate enough to save us about $20 million in fuel costs over our entire system in the last five years. We have had head-to-head competition for electricity service since 1973, and I can tell you that innovation is the key to staying ahead."

The twist to Dahlberg's story is that these engineers had to work around company policy, which had strictly regulated the use of data processing equipment. "They found they couldn't buy a little personal computer, so they wrote it up as a refrigerator or some such nonsense on the purchase order. The point is, we had inadvertently set up roadblocks to innovation within our own company in a well-intentioned effort to normalize operations. This helped to wake us up, and I think today we have a new attitude—we believe that changing everything for the better has become everyone's job."

Dahlberg provided a sampling of innovations on the supply side of Georgia Power's business, ranging from coal quality assessment techniques to preventive maintenance programs to fiber-optic communication systems. "Our automatic governor controls help us smooth out starts and stops, increasing fuel efficiency and cutting maintenance costs. We're even using peanut hulls. It's a useful fuel, and burning it helped us maintain a customer who would have gone to cogeneration."

To Dahlberg, these are examples of the kinds of things that make a difference. "In the Southern Company system—a $25 billion investment, half of it in Georgia—everything needs to work more efficiently at lower cost to make us more competitive."

Jack Kaslow, executive vice president and chief operating officer of New England Electric System, added a similar list of recent accomplishments in his utility aimed at cost control and improvements in operation—targeted chlorination for condensers, an improved intake screen that allowed a coastal plant to move back to open-cycle operation, and managing the installation and operation of a multiterminal dc link to Canada, to name a few. "They may not be headline grabbers," he said, "but they mean savings for our customers."

Kaslow is chairman of EPRI's Research Advisory Committee, which puts him at the head of a 600-plus-person structure set up to help guide EPRI's program and transfer technology back to member utilities. From his perspective in shaping and monitoring one of the pioneering R&D consortia in the nation, he has come to view innovation broadly.

"Innovation," he told the seminar participants, "is the part of corporate culture that makes things happen." And some of the innovations his company is proudest of are things they helped initiate beyond the meter. Drawing on prepared remarks by Sam Huntington, former CEO of NEES who died tragically just before the seminar, Kaslow said, "It was the creative tension between regulators and utilities that opened up demand-side programs. The shift in utility focus from kilowatthours to service was a significant institutional innovation that led in turn to an explosion in technological and marketing innovations."

NEES's Lodestar Program, developed to do statistical load analysis, was soon licensed to other utilities around the nation. NEES worked with EPRI to develop equipment that could monitor load patterns nonintrusively—without the need for hard-wiring inside the home or business—and like many utilities around the nation, it set up a wide range of programs to sell conservation. In one notable program, NEES developed a dealer rebate program to price energy-efficient lighting competitively with traditional bulbs and ballasts, and succeeded in creating an immediate market in its service territory where none existed before. □

to change our ways, tackle the deficit, tighten our belts, and retool for the future. And Hatsopoulos reminded everyone that, culturally, economic behavior is not immutable.

"Yes, consumption is partly a cultural problem," he said. "But culture can change. Ours changed before and it can change again, as have others. Remember, before World War II Japan saved less than or the same as the U.S. (about 5% of GNP). After the war the Japanese changed their culture in order to rebuild their industry, enforcing savings and sacrificing a lot to do this, including housing and infrastructure. As we put our house in order, the Japanese should be able to take the money they now lend us and build up their country." The prospect he offered was one of two divergent but intertwined economies moving toward some stable central position between today's extremes of consumption (U.S.) and savings (Japan).

'The solution for our economy is to get on with national savings. The first problem is to reduce the federal deficit; the second is to increase private savings. Once you get that wheel in motion, you can afford to change the tax code to reward savings rather than consumption.'

Hatsopoulos

Managing the innovation process

The management of technology is in a rapidly evolving, almost experimental state today. Entrepreneurs inside and outside corporate America who have experimented with new management forms have helped to infuse larger organizations with some of the special vitalities of small business. Roland Schmitt described the evolution in technical management from the perspective of his years as head of R&D at General Electric. "We used to think products grew directly out of the lab. This was a linear model, sort of like a relay race, where basic research would come up with something and then pass to the group responsible for commercial applications, and they in turn would pass to the development group, and on to marketing, and so on.

"This approach got replaced with the market-driven model, where we sort of reversed the process. Instead of asking basic research to come up with the innovations, we asked the marketing people, 'What do the customers want and need?' I call it 'just-in-time technology.' It doesn't work either, but it is still very popular in the United States. Remember, Japan has never fallen into either of these traps: they have never had basic research labs or marketing organizations. Their systems of technology innovation are more unified throughout."

Schmitt said the best businesses today have moved toward an approach involving strategic linkage of technology to long-term business objectives, something he said is analogous to "aiming at a target without a bull's-eye." He added, "This means investing in technology before a precise marketing target is identified. The early investment is not a freewheeling foray into the most exciting ideas of the scientists, but rather a disciplined investment in areas that are solidly linked to the business strategy."

This approach sounds not too dissimilar to the targeted industrial strategies that the Japanese have modeled so effectively and that are now being copied worldwide. At any rate, Schmitt said that once the strategic linkage is confirmed, the steps of managing innovation are clear-cut. "First, you acquire the technical skills, talents, and expertise you need in a strategically important area. This step is not too expensive. Next, you select program objectives based on a still imprecise target and pull together a multifunctional team to carry them out. As you move the innovation forward, the costs and commitment go up, and the multifunctional team is reconvened time and time again to bring the market bull's-eye into focus."

This notion of an imprecise marketing target reminded Tom Byrer of a firm in Japan that is working on ceramic scissors. "Not that anyone wants a pair of ceramic scissors, mind you. They're just trying to learn about processing ceramics. We find it curious because we tend to think you have to have a final product firmly in mind."

The small multifunctional team mentioned by Schmitt was a theme picked up and described in various ways by several participants. The key seemed to be avoiding the historical problems of functional disconnection by combining functions—R&D, manufacturing, marketing, finance, and so on—at the outset into small units responsible for all stages of the innovation process.

Harry Coover, retired vice president of Eastman Kodak Chemicals, described just such a system of "programmed innovation" that he helped to put in place for Kodak Chemicals and more recently for Loctite Corporation, a specialty chemicals manufacturer. "The total business of the corporation is subdivided into business areas, then further subdivided into small business units. Each SBU is managed by a small, highly focused, entrepreneurial business team that has learned that success in innovation requires it to think, plan, and act strategically. The principals of the SBU are R&D, marketing, sales, finance, and manufacturing specialists, plus a person skilled in the techniques of technology forecasting. Consultants are brought in whenever necessary, and the SBUs have at their disposal centralized service and support functions. Administratively, an SBU's reporting relationship can change over time—initially it may report to R&D, later to marketing—depending upon the stage of innovation."

The SBUs in Coover's scheme have been clustered into broad strategic business areas that try to juggle a portfolio of products and projects at all times—some to maintain market share, some to increase market share, and some involving so-called "stretch" positions, where opportunities have been identified but where product plans have not yet jelled. Beyond the stretch position is still another area of exploration that Coover simply calls the "company goal," a direction the team would like the business to go, but where even the opportunities for innovation are not yet clear.

A key result of this new structure in Coover's mind is that "technical management has been repositioned—assigned a major responsibility for defining the future of the company. Technical strategy has been integrated with business planning strategy. R&D has been coupled with management, marketing, and manufacturing."

The programmed-innovation process, which evolved slowly over a period of 20 years at Eastman Kodak Chemicals, had taken firm root by the late 1970s, according to Coover. Product introductions accelerated; 320 new products were introduced from 1980 to 1984 alone, while sales grew from $1.8 billion in 1979 to $2.5 billion in 1984. At Loctite, where programmed innovation has been in place for only two years, sales grew from $230 million in 1985 to over $400 million in 1988 after five years of relative stagnation.

Reaching outside the corporate world

The corporate world is not the only institution in the United States currently reexamining its role in managing technology innovation. Universities and the national labs, which play key roles in basic research, are also taking a look. Roland Schmitt, having recently made the move from corporate R&D management at GE to the presidency of Rensselaer, is particularly interested in improving the transfer of technology from universities to industry. "The best technology transfer begins with the education of scientists and technologists. Students, once introduced to it, are good at it. The linkage flavors their whole educational experience and instills both new respect and new skills for tech transfer."

In Schmitt's view, the academic ties to industry are already strong in the United States—"We're ahead of the Japanese and equal to Europe," he said, because of the history of faculty consulting, undergraduates working in industry, and industrial employees returning for training. But in the last decade, entirely new modes of interaction have begun to appear that offer a glimpse of the future—such things as "campus-based 'incubators,' university-based industrial parks, and precompetitive R&D consortia.

"A key result of programmed innovation is that technical management has been repositioned—assigned a major responsibility for defining the future of the company. Technical strategy has been integrated with business planning strategy."

Coover

"At Rensselaer, we set up campus-based incubators in the early 1980s to provide an environment for startup companies. We trade low-cost space for a modest amount of stock, and provide ties to the science, engineering, and management schools at the university. About 20 companies that have come out of this program are still viable. Stepping up from that level, we also have a 1200-acre industrial park that provides a home for those graduating from the incubator plus others."

Still more broadly, Schmitt is intrigued with the movement toward R&D consortia, such as MCC and Sematech, which have emerged in recent years as a result of changes in the antitrust laws. "Pooling industrial research efforts at the precompetitive stage is a valid concept for U.S. industry to follow. And linkage of these consortia to campuses by locating in nearby parks would have many, many advantages for the nation."

Turning to the national labs, Schmitt led a brief discussion of their particular role in American science and technology, concluding that in his view, "they are not going to work as corporate labs for the nation—they just can't be very effective in launching new programs for the purposes of developing commercial products." Others remarked on the great analytical capabilities of the labs, and the possibility of their playing an expanded service role for the nation. Schmitt sees the possibility of the labs taking on a more active technology transfer role by "establishing vigorous programs of licensing of the technology they develop, and supporting entrepreneurs who pick up on their work."

Utilities as a bridge to industrial development

Utilities also have a special role to play in technology innovation—if for no other reason than that the overwhelming majority of innovative technology is pow-

❛At our Technology Application Center, we don't provide equipment; we provide a place for manufacturers to bring their equipment, provide someone to demonstrate it, and bring our customers in. It pays off.❜

Dahlberg

ered by electricity. Ted Carlson, chairman of the board of Central Hudson Gas & Electric, extended this concept historically, pointing out that "the history of this nation is one of constant growth in the uses of electricity—in the home, in business, in industry—and constant revitalization of our economy. The future of this industry and of electricity research has to be as broad as society itself."

Utilities, like other industries, have moved much closer to their own markets, and have begun to view technology innovation as a continuum of efficiency improvements on both sides of the meter—a single system from fuel processing to electricity supply to customer usage. The results in some parts of the industry have been impressive, bringing with them a new respect and a new excitement about the role that innovation, both technological and institutional, can play in spurring American competitiveness.

Many utilities are now positioned as full-service suppliers. This means their customers' problems become their problems. And for utilities working with in-

Speakers

Tom Byrer, *Senior Vice President*
Battelle, Columbus Division

Harry W. Coover, *Vice President (retired)*
Eastman Kodak Chemicals

A. W. Dahlberg, *President*
Georgia Power Co.

George Hatsopoulos, *Chairman and President*
Thermo Electron Corp.

John Kaslow, *Executive Vice President and Chief Operating Officer*
New England Electric System

Nathan Rosenberg, *Professor*
Dept. of Economics, Stanford University

Roland W. Schmitt, *President*
Rensselaer Polytechnic Institute

Participants

Sy Alpert, *EPRI Fellow*

Edwyna G. Anderson,* *Commissioner*
Michigan Public Service Commission

Walter S. Baer,* *Director*
Advanced Technology, Times Mirror Co.

Richard E. Balzhiser, *President and CEO*
EPRI

Robert W. Bratton
RWB Associates

Edward F. Burke, *President*
Canadian Connection, Ltd.

Wilson K. Cadman, *Chairman and President*
Kansas Gas and Electric Co.

Theodore J. Carlson, *Chairman*
Central Hudson Gas & Electric Corp.

Anne P. Carter,* *Chairman*
Dept. of Economics, Brandeis University

Thomas V. Chema,* *Chairman*
Ohio Public Utilities Commission

Richard Claeys, *Director*
Corporate Communications, EPRI

John V. Cleary, Jr., *President and CEO*
Green Mountain Power Corp.

Floyd L. Culler, *President Emeritus*
EPRI

Charles H. Dean, Jr., *Director*
Tennessee Valley Authority

O. Mark DeMichele, *President and CEO*
Arizona Public Service Co.

John B. Driscoll,* *Commissioner*
Montana Public Service Commission

John F. G. Eichorn, Jr., *Chairman and CEO*
Eastern Utilities Associates

Dennis G. Eisnach,* *Chairman*
South Dakota Public Utilities Commission

E. James Ferland, *Chairman, President, and CEO*
Public Service Electric & Gas Co.

Alex Fremling, *Deputy Director*
Business Management Group, EPRI

Edythe J. Gaines,* *Commissioner*
Connecticut Dept. of Public Utility Control

Michehl R. Gent, *President*
North American Electric Reliability Council

Dominic Geraghty, *Assistant to the President*
EPRI

John H. Gibbons,* *Director*
Office of Technology Assessment

Charles H. Goodman, *Vice President*
Southern Company Services

Wolf Häfele, *Chairman*
Kernforschungsanlage Jülich GmbH
Federal Republic of Germany

George M. Hidy, *Vice President*
Environment, EPRI

Lawrence Hobart, *Executive Director*
American Public Power Association

Stanley W. Hulett,* *Commissioner*
California Public Utilities Commission

Bruce G. Humphrey, *Assistant to the President*
Strategic Planning, Edison Electric Institute

Gordon C. Hurlbert,* *President*
GCH Management Services, Inc.

James J. Jura, *Administrator*
Bonneville Power Administration

Fritz Kalhammer, *Vice President*
Exploratory Research, EPRI

Milton Klein, *Vice President*
Industry Relations and Information Services, EPRI

Robert K. Koger,* *Commissioner*
North Carolina Utilities Commission

Girts Krumins, *President and CEO*
Colorado-Ute Electric Association

Sharon Luongo, *Senior Conference Coordinator*
EPRI

Brian MacMahon, *Professor*
Dept. of Epidemiology, Harvard University

George A. Maneatis, *President*
Pacific Gas and Electric Co.

Gene Mannella, *Director*
Washington Office, EPRI

Lord Walter Marshall, *Chairman*
Central Electricity Generating Board, England

Katherine A. Miller, *Manager*
Strategic Planning, EPRI

C. Burton Nelson, *Director*
Regulatory Relations, EPRI

Norman E. Nichols, *Assistant General Manager, Power*
Los Angeles Dept. of Water & Power

Larry W. Papasan, *President and CEO*
Memphis Light, Gas & Water Division

J. Dexter Peach, *Director*
General Accounting Office

John W. Rowe, *President and CEO*
Central Maine Power Co.

Richard Sternberg, *Manager*
Hazardous Waste and Fuel Supply
National Rural Electric Cooperative Association

Stephen J. Sweeney, *Chairman, President, and CEO*
Boston Edison Co.

John J. Taylor, *Vice President*
Nuclear Power, EPRI

Grant P. Thompson,* *Executive Director*
League of Women Voters

Victoria J. Tschinkel,* *Senior Consultant*
Landers, Parsons & Uhlfelder

Stewart L. Udall,* *Attorney at Law*

Andrew Varley, *Vice President*
American Electric Power Co.

Judith B. Warrick,* *President*
Green Lane Enterprises

Thomas C. Webb, *President and CEO*
Central Vermont Public Service Corp.

Dean G. Wilson,* *President and CEO*
Blaw Knox Corp.

Herbert H. Woodson,* *Acting Dean*
University of Texas

Kurt Yeager, *Vice President*
Generation and Storage, EPRI

Richard W. Zeren, *Director*
Membership Development, EPRI

*Advisory Council member

dustrial customers, this now puts them in the business of supplying not only kilowatthours and customer service but technology innovation itself. Many seminar participants were eager to see utilities pursue this broader role of regional and even national economic development.

Tom Byrer fondly recalled a pivotal conversation at Georgia Tech during the formative stage of the Center for Materials Fabrication at Battelle. "The director of the Georgia technology extension service explained their program of using an agent in every county—much like an agricultural extension agent. Local industry can call him up and ask him any question, and he'll go back to the university to try to find a solution to the problem. The director then went on to say, 'Now if you could somehow get the electric utilities involved in this kind of activity, you would have a ready-made network to transfer technology to industry, one that nobody else could ever afford to put in place. There really isn't any other institution that has that kind of all-encompassing network.' "

With that notion, Byrer went back to Battelle to build up the first of three centers sponsored by EPRI member utilities to assist their industrial customers with the application of new technology. "We have been up and running at the CMF for five years now, and we have 60 utilities in 31 states participating in the program. With this foundation, we can begin to build the critical bridge between what utility customers want and need and the tremendous wealth of technical resources we have in this country."

Similar bridges are being built around the country by enterprising utilities and local industry, according to Jack Kaslow, executive vice president and chief operating officer of New England Electric System. Kaslow described a unique collaboration called the Southern New England Initiative, in which NEES and other utilities in the region joined with EPRI and with the state regulatory commissions and economic development agencies from the states of Rhode Island, Massachusetts, and Connecticut. "The program was to bring the experts to our customers, who were selected from a variety of key industries in our area, including electroplating, plastics, shipbuilding, jewelry manufacturing, fish processing, and steel fabrication. The initiative identified some real technological improvements, ranging from laser-directed water spray for fish cutting to more efficient preheating techniques in welding activities."

"This was a significant cooperative effort between government, utilities, and EPRI," said Edward Burke, president of Canadian Connection, Ltd., and one of the prime movers behind the initiative. "American industries, particularly those with small R&D budgets, are hungry for assistance and advice. We took off-the-shelf technology and got it out into the field. The effort paid off."

Similarly, throughout the Southern Company system, formal networks have been established to boost regional economic development. In 1984 Georgia Power set up its Energy Planning Center to provide seminars, hands-on exhibits, and information for business and industry; in 1987 it added the Technology Application Center to test and demonstrate electrotechnologies for industry. This facility is now considered among the premier end-use centers in the country. According to Bill Dahlberg, president of Georgia Power, "We don't provide equipment; we provide a place for manufacturers to bring their equipment, provide someone to demonstrate it, and bring our customers in. It pays off. We added 37 MW of new load last year when customers saw demonstrations of electric cooking units. And on the industrial side, we have already successfully applied radiofrequency heat processing for yarn, carpets, and vinyls, and infrared processing for composite materials."

The advantages of this kind of demonstration center can't be overestimated, according to Byrer, who has seen too many cases of people returning from trade shows with robots and machine tools they don't know how to adapt. "We need more demonstration sites of the kind they have at Georgia Power. We need them all around the country. They're a place where people can come and sit down and get familiar with a new technology, so that when they take it into their plant, it is not so foreign to the operation."

Utility industrial development activities in the state of Georgia point toward the future—one that recognizes the economic role utilities can play by actively channeling new investment opportunities and advanced technology to their customers. Just how far utilities can go, and whether they will in the future be linking up routinely with state or regional development groups, is not yet clear. Nevertheless, utilities recognize the advantages of long-term investment in their service territories. And they are coming to view themselves as suppliers of innovation just as certainly as kilowatthours. ■

"It was the creative tension between regulators and utilities that opened up demand-side programs. The shift in utility focus from kilowatthours to service was a significant institutional innovation that led in turn to an explosion in technological and marketing innovations."

Kaslow

Startup of the 160-MW fluidized-bed unit at TVA's Shawnee generating plant marks another milestone in the development and commercialization of clean coal combustion systems. The technology could establish the foundation for widespread repowering of existing coal-fired plants in the next decade.

Fluidized Bed Fires Up at TVA

Add Paducah, Kentucky, to the map of utility clean coal technology demonstration sites. The city, along the Ohio River at the edge of the state's western high-sulfur coalfields, now boasts the world's largest utility-scale fluidized-bed boiler.

Operating since last fall, the 160-MW unit delivers steam to one of 10 turbine generators at the Tennessee Valley Authority's Shawnee plant. The $232 million project was built with major funding from TVA, EPRI, Duke Power, the commonwealth of Kentucky, Combustion Engineering, the U.S. Department of Energy, and the Atmospheric Fluidized Bed Development Corp., a consortium of railroads, coal producers, and utility companies. Several years of tests on this and other large operating utility fluidized-bed boilers are expected to prove that the rational route to emissions control for coal-fired utility and industrial plants lies in advanced combustion processes that can enhance both plant performance and environmental protection.

But the Shawnee plant's demonstration of atmospheric fluidized-bed combustion (AFBC) could have more direct impact on industries and regions with a stake in the nation's abundant high-sulfur coal reserves. Because fluidized-bed boilers can burn a variety of coals and other solid fuels with consistently good performance, AFBC could make it economically feasible to use many coals that have been nearly abandoned as generating fuel.

Some years ago, TVA's Shawnee steam plant (built in the mid-1950s to power the government's mammoth uranium enrichment complex nearby) was forced to stop burning the local Kentucky No. 9 coal, which has about 4% organic sulfur, in favor of lower-sulfur coal from outside the region as an alternative to building scrubbers to meet emissions limits. Today, Shawnee is once again burning local coal—in the new AFBC boiler. The plant is designed to meet current federal emissions regulations, with 90% sulfur dioxide removal and a near total elimination of nitrogen oxides, both of which are implicated in acid rain—but without the efficiency and cost penalties or sludge disposal issues associated with massive back-end flue gas desulfurization (FGD) systems.

Called a choice for the future

"The AFBC demonstration will be used to refine and enhance a technology that is vital to the nation's energy future," said TVA Chairman Marvin Runyon at a rainy dedication ceremony last November. AFBC technology could be particularly vital to TVA, one of the country's largest buyers of coal, which fuels about 70% of the federal utility's power generation. As is the case for most of the utility industry, many of TVA's aging coal-fired plants are candidates for life-extension and repowering—capital-conserving retrofit options for which AFBC appears well suited. A 1983 EPRI study put the conversion potential nationwide at 200 plants, representing 28,000 MW.

Runyon called Wendell Ford, Kentucky's senior senator and the keynote dedication speaker, "the major force in getting the project off the drawing board" and securing $30 million in federal appropriations for it over the last several years.

Ford, for his part, tossed aside a prepared speech and praised the spirit and skill of the workers who built what others called perhaps the most-advanced coal-fired plant in the country. "The answer to energy independence is right here," said Ford, describing the new AFBC unit as a symbol of commitment to affordable coal-fired electricity and enviromental protection for future generations. Rather than high-sulfur coal's being regulated out of use in favor of low-sulfur varieties, Ford noted, wider utility adoption of fluidized-bed technology in the 1990s could stabilize what has traditionally been a boom-or-bust eastern mining industry by ensuring long-term markets for high-sulfur coal.

Other speakers told the crowd of several hundred that the Shawnee demonstration is proof of the utility and coal industries' commitment to control combustion emissions with better efficiency and at lower cost than with add-on FGD systems. Among them, EPRI President and CEO Richard Balzhiser called the project "a true centerpiece of our nation's clean coal effort," and the start of operations "another milestone in our quest on behalf of all utilities for clean technologies for the direct use of coal. Now we begin the next phase," he continued, "which will permit us to learn and to understand better what is needed for widespread commercial adoption."

Paul Wieber, the associate director of DOE's Morgantown, West Virginia, Energy Technology Center, noted that the Shawnee AFBC unit "beats all New Source Performance Standards" for pollutant emissions and also produces less carbon dioxide—implicated as a contributor to global greenhouse warming—than a conventional pulverized-coal boiler of comparable size equipped with scrubbers.

Key to the AFBC unit's low emissions is the combustion process, in which ground coal and limestone are mixed (at a ratio of about 2.8 to 1) and injected through ports in the bottom of the 13-story boiler to maintain a roiling bed of burning solids. The limestone reacts with and absorbs sulfur released from the coal to form calcium sulfate, a dry gypsum-like material that drains from bottom hoppers and can be used in fertilizers and construction material. In-bed combustion temperatures of around 1550°F are about half those of conventional coal boilers, thus inherently limiting the formation of nitrogen oxides, which is air- and temperature-dependent.

Built in about three years by Fluor Constructors alongside the old No. 10 boiler (which was not dismantled), the AFBC unit, designed by Combustion Engineering, uses the plant's existing coal-handling equipment and turbine generator; the coal- and limestone-feeding, fly ash recycle, and other systems are new.

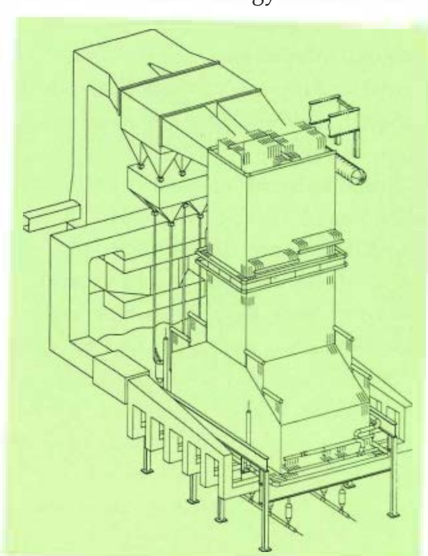
As a retrofit, the unit cost about $950/kW to install, not including certain development and first-of-a-kind costs, according to Arnold Manaker, TVA project manager.

EPRI expects most retrofits would fall into the $500–$1000/kW range; a completely new plant today could be expected to cost typically about 5–10% less than a conventional unit equipped with scrubbers. The main capital cost saving is in the elimination of a flue gas scrubber. This saving is expected to increase as fluidized-bed technology matures commercially.

The potential for operating cost savings lies first in AFBC's fuel flexibility. The savings would vary according to a utility's ability to exploit the flexibility by, for example, avoiding long-term contracts in favor of the spot market or low-grade fuels. The ability to switch fuels and to burn coal of nearly any quality could mean savings of as much as 25–50% in the cost of fuel. Ensuring the engineering basis necessary to achieve these fuel cost savings is at the heart of the AFBC demonstration program.

More than a demonstration

As originally conceived several years ago, the Shawnee AFBC plant was to be the utility industry's principal demonstration of bubbling fluid-bed technology under EPRI aegis, culminating over a decade of R&D with smaller prototypes. The program was intended to provide a confident design and operating base for utility application of the technology in both new



Shawnee AFBC boiler

A Day of Dedication at TVA

National, state, and local officials joined executives of various sponsoring companies and organizations, including EPRI, at TVA's Shawnee steam plant in Paducah, Kentucky, on November 18, 1988, to celebrate the completion and startup of the atmospheric fluidized-bed demonstration. The new 160-MW AFBC unit was installed alongside the old No. 10 boiler and delivers steam to the existing turbine generator. Limestone mixed with the coal and fluidized by air in the boiler captures 90% or more of the sulfur oxides directly during combustion. In-bed temperatures about half those of typical coal-fired units inherently limit the formation of nitrogen oxides.

TVA Chairman Marvin Runyon

EPRI President and CEO Richard Balzhiser

November 18, 1988

Senator Wendell Ford of Kentucky

plant and repowering applications at sizes up to at least 300 MW.

Since then, however, several other suppliers and utilities have taken the plunge with a variety of fluid-bed systems significantly different in various ways from the Shawnee atmospheric pressure, bubbling-bed unit. These installations complement the Shawnee project and significantly expand the AFBC information base available to utilities, suppliers, and architect-engineers.

Fluidized-bed units are now available from all the major fossil fuel boiler manufacturers supplying the American utility market. Such units now operate on utility systems in Colorado, Kentucky, Minnesota, and North Dakota; others are under construction in Texas and Ohio and proposed for West Virginia. EPRI funds substantial test and documentation programs at nearly all of the currently operating units. Some projects, such as the Colorado-Ute Nucla circulating AFBC prototype, American Electric Power's pursuit of pressurized fluidized-bed combustion technology, and the Southwestern Public Service circulating AFBC, are also supported under the federal government's Clean Coal Technology Demonstration Program.

In certain respects, the Shawnee unit is unique among the projects, since it represents a large-scale development facility that is the latest in a series of major R&D efforts in fluidized-bed technology by EPRI and its contractor-suppliers. First came bench-scale work in the mid-1970s, then a 2-MW facility in Ohio, followed by a 20-MW prototype at the TVA Shawnee plant (which is now to be used to test a hybrid concept in fluidized beds). These efforts progressively laid the technological and engineering foundations for the 160-MW demonstration.

"The Shawnee fluidized-bed project was established at the outset as a technical demonstration, one that recognized the technology was not mature," notes Kurt Yeager, EPRI vice president and director of the Generation and Storage Division. "That is why it was built as a collaborative venture by a number of sponsors and why its design has tried to take into account risks and uncertainties by providing corresponding flexibility in a number of areas, such as the coal-feeding systems. I believe the Shawnee project has proceeded the most realistically in terms of recognizing the prototypical status of AFBC technology today.

"Most of the other AFBC projects at the 100-MW scale have been straight commercial ventures, even though the technology was prototypical for utility application. As a result, some suppliers have taken a calculated risk on their learning curve to gain market advantage. Fortunately, the problems and issues that have arisen were largely anticipated with a new system and are being resolved in the field.

"This underscores the importance of the patient utility AFBC technology development program implemented by EPRI and others on an industrial scale over the past 15 years," adds Yeager. "As a result, many of the issues in AFBC commercialization center on the auxiliary systems and components rather than the fluidized bed itself. The Shawnee plant has been instrumented and will be tested more extensively than any other fluidized-bed project. With respect to bubbling-bed technology, it is designed to provide the key information necessary for utilities to quantitatively assess its commercial future and specify commercial orders."

Yeager believes that, because of their relative cost-effectiveness in repowering existing boilers, fluidized-bed units could prove to be a leading generating technology choice of utilities as capacity is increased in the 1990s. "Over the next decade at least, most of the new capacity that will be added will be either gas turbine peaking capacity or repowering and performance extension of existing coal-fired units. I expect fluidized beds are going to be the backbone of that repowering wave," Yeager says.

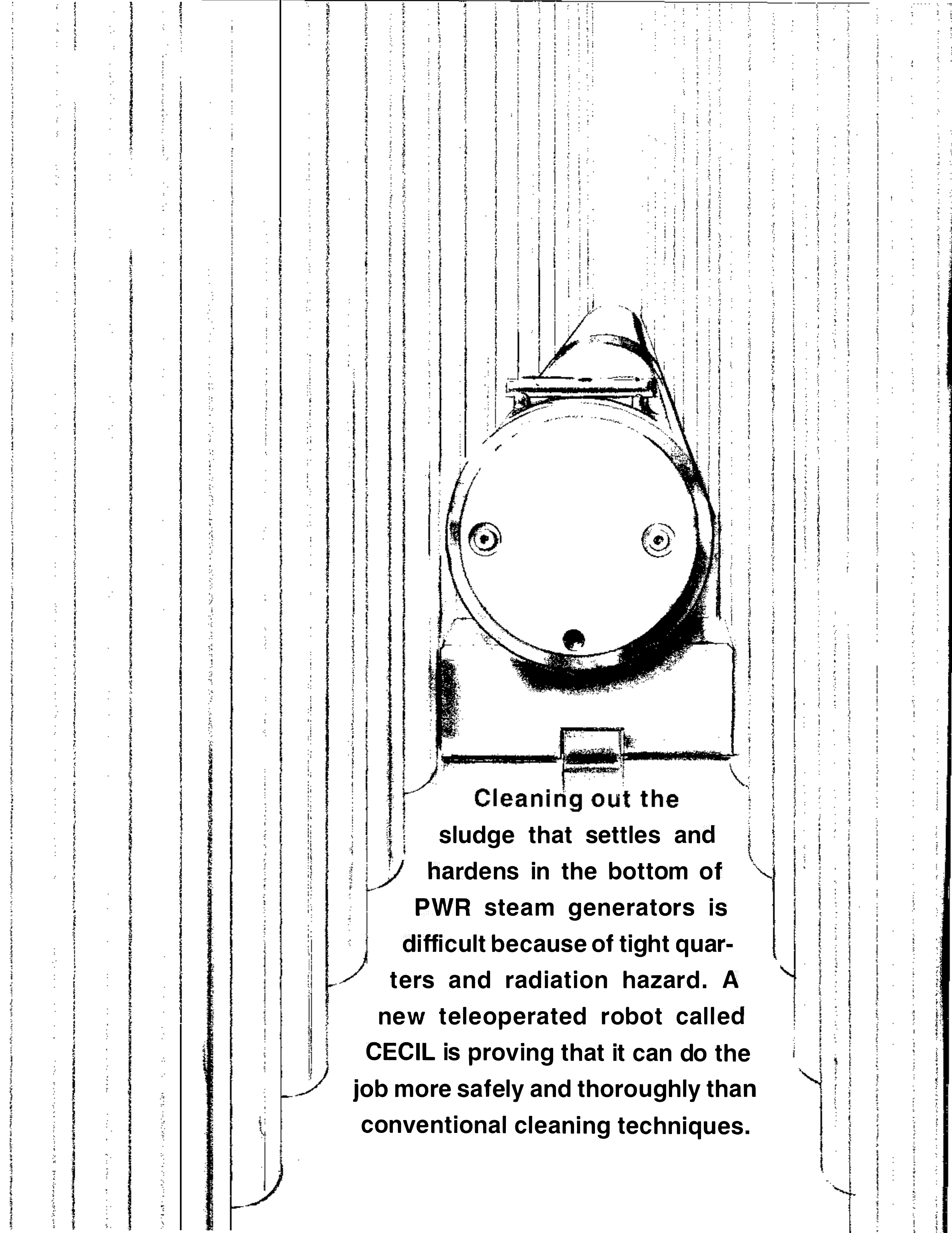
An answer to several problems

The glowing orange-red fire visible through ports in the Shawnee 160-MW AFBC boiler, then, represents more than just another TVA, Duke Power, or EPRI demonstration, more than one working solution among others to the problem of coal-fired utility emissions, and more than a collaborative industry-government R&D effort. The fire of this and other utility-scale fluidized-bed units operating or now being built represents a solution to several problems facing utilities as the 1990s loom, a solution that has evolved over the past two decades and has matured to the edge of broad commercial acceptance. Operating results from all the fluidized-bed projects will be closely watched in the years ahead and will play a decisive role in upcoming capacity expansion decisions.

"With the fluidized-bed plants that are operating or being built today, we have the first commercial generation from the utility industry's advanced clean coal technologies that were initiated for development in the early 1970s," explains Yeager. "But they certainly don't represent the culmination of the technology or the last demonstrations that we're going to be involved with. There will continue to be opportunities for further development in fluidized beds and coal conversion, as well as in other generation and storage technologies.

"With the current projects, EPRI and the utility industry have moved coal utilization technology out of a long period of stagnation onto a new plateau of development and commercial innovation. In terms of their development potential, the new fluidized-bed plants today are somewhat analogous to the first pulverized-coal plants 60 years ago. Utilities and the manufacturers have taken conventional pulverized-coal technology about as far as it can go. Fluidized-bed technology has just begun its development cycle." ■

This article was written by Taylor Moore.



Cleaning out the sludge that settles and hardens in the bottom of PWR steam generators is difficult because of tight quarters and radiation hazard. A new teleoperated robot called CECIL is proving that it can do the job more safely and thoroughly than conventional cleaning techniques.

SLUDGEBUSTER FOR STEAM GENERATORS

Crawling down a narrow lane through a forest of nickel-alloy tubes, a cylindrical robot reaches its destination and stops, extending spherical feet to anchor itself in place. The robot inserts a flexible, belt-shaped band called a flex-lance into the ⅜-inch gap between two columns of tubes. As the flex-lance snakes into the tube forest, its tip unleashes water jets targeted at a mass of sludge nestled among the tubes, a mass that has resisted all previous attempts to dislodge it. The robot withdraws the flex-lance and advances to the next tube gap to repeat the process. Seventy-five feet away, an operator sitting at a workstation controls the procedure and monitors the robot's progress on screens that display a video picture from the miniature camera mounted in the flex-lance's tip, as well as the precise position of the lance inside the tube bundle.

The prototype robot is called CECIL, for Consolidated Edison Combined Inspection and Lancing system. Developed under funding from EPRI, the Empire State Electric Energy Research Corp. (ESEERCO), and Consolidated Edison Co. of New York, the robot is a new weapon in the power industry's war on sludge. Equipped with an electronic eye and armed with water jets, CECIL can inspect and clean areas deep within pressurized water reactor (PWR) steam generators, where human access is prohibited by tight spacing and high radiation levels. Con Edison estimates that CECIL will save the utility at least $100,000 per refueling outage, while reducing radiation exposure to personnel.

Tenacious, inaccessible sludge

A PWR steam generator works like a giant teakettle, using heat from the reactor core to make steam. The generator's cylindrical steel vessel encloses thousands of ¾-inch-diameter nickel-alloy tubes, arranged in an inverted-U configuration about 30 feet high. (The dimensions quoted are for a Westinghouse Model 44D steam generator; dimensions may vary with steam generator design and supplier.) Water heated in the reactor core—kept under pressure to prevent boiling—runs through these tubes, heating secondary water circulating inside the vessel. The secondary water, being at a lower pressure, boils to produce steam to spin turbines. Sludge forms when particulate impurities suspended in the feedwater coalesce and concentrate as the water boils, much as scale develops in a teakettle.

The principal culprits are oxides of iron and copper from the secondary-side components and piping; oxides of nickel, zinc, silicon, and calcium may also be present in small amounts. The concentrated impurities settle in low-flow regions, especially on the tubesheet, the massive slab that supports the U-tube assembly, where they may form a pile 10 inches high or more. Sludge deposits vary in size, composition, and hardness, depending on a particular plant's design and construction materials, its feedwater chemistry, and its operating characteristics. The deposits may be soft and silty, firm and sticky like peanut butter, or harder than concrete. A PWR steam generator may play host to all three types, in quantities ranging from 25 pounds to 2 tons or more.

Because it forms a layer between the tube walls and the surrounding water, sludge inhibits heat transfer, which can reduce generating capacity. A more serious problem, however, is that sludge deposits contain voids that concentrate aggressive chemicals such as chloride and sodium hydroxide, which attack the tubes, causing corrosion and cracking. If this damage is allowed to run unchecked, the corroded tubes must be plugged or sleeved; if many tubes are damaged the whole steam generator may have to be replaced. These remedies are neither easy nor cheap. Plugging or sleeving tubes during a repair outage can cost up to half a million dollars. The cost of replacing a steam generator, including purchasing replacement power, can run several hundred million dollars.

For these reasons, most utilities operating PWR plants inspect and clean their steam generators during refueling or maintenance outages. But the difficulty of gaining access to the interior of the tube bundle limits the effectiveness of current tools and techniques used for inspection and sludge removal. Access to the interior just above the tubesheet is limited to inspection ports—6 inches or less in diameter—in the vessel wall. Close confines make manipulation of hand-held tools awkward, and radiation severely limits the amount of time an operator can spend in the area.

The most common sludge removal method is water lancing, which involves hosing out the generator during a refueling or maintenance outage. Typically, the water nozzles are positioned either in the blowdown lane—the narrow passage between the legs of the U-tube bundles—or in the annulus around the tubing, and their spray is directed into the bundles. This technique may be partially effective in removing softer sludge, but it does not remove the more tenacious hardened deposits because the water jets lose their punch a short distance from the nozzle. After the first few tube rows, the jets lack the energy required to break up sludge deep in the tube bundle.

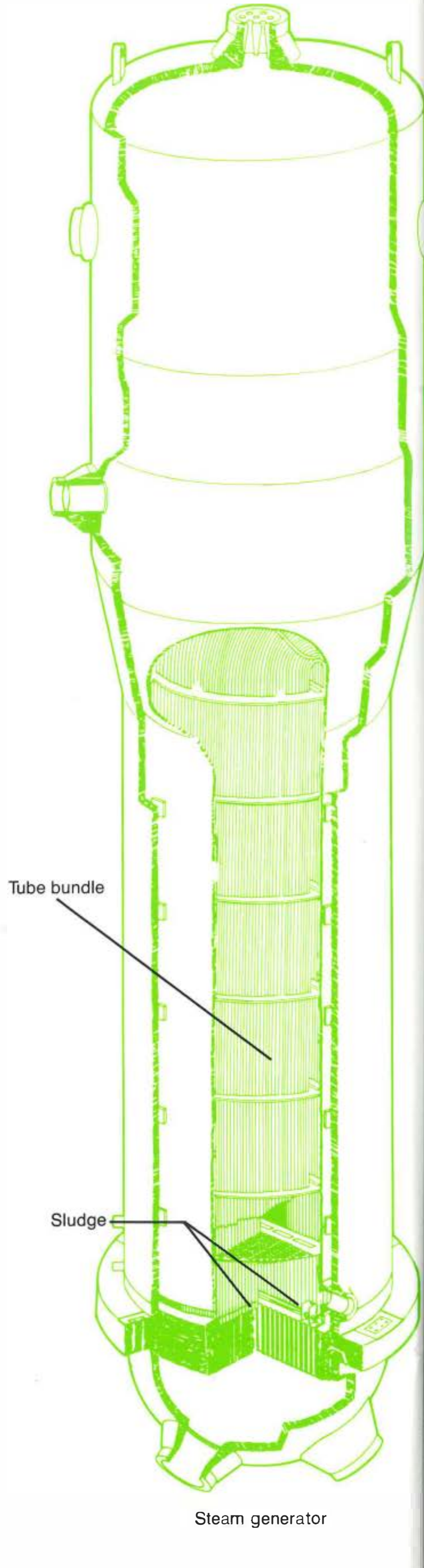
Also, it's difficult to determine how much sludge remains after lancing. "You might lance out 500 pounds of sludge and assume that your steam generator is clean," says Lamar Williams, a project manager in EPRI's Nuclear Power Division. "However, the real issue is not how much sludge was removed but how much remains inside the steam generator. Unless you can take a good look inside the tube bundle, you have no idea if there's one pound or a thousand pounds of sludge still inside." Although some utilities have used fiber-optic probes or eddy-current testing to do inspections, neither technique has yielded consistently satisfactory results.

Recognizing that sludge was a source of expensive damage to steam generators and that some PWR utilities weren't satisfied with existing inspection and cleaning procedures, EPRI, Con Edison, and ESEERCO sponsored a project to improve these systems. The project's first step was a survey of utility experience and vendor practices in inspecting and removing sludge from steam generators. "We didn't want to reinvent the wheel or develop something that would duplicate what was already available," says Williams. "We chose to study the existing tools and practices to identify areas where improvements could be made before going ahead with any development effort. When the request for project authorization passed through EPRI's Nuclear Power Division, we also sent it through the other, nonnuclear divisions with the idea that they might provide some fresh thought or suggest some related technology that could be useful. Through that process we identified a technology development company in Massachusetts called Foster-Miller, which had developed some innovative material removal technology for the Electrical Systems Division. They came up with a concept, and a way of turning it into hardware, that evolved into CECIL."

Accurate and repeatable access

The survey revealed two basic needs: a better way to inspect the interior of the tube bundle, and a means to deliver water jets directly to the hard sludge deposits. Foster-Miller came up with the concept of a thin, flexible band that could pass through the narrow gaps between tubes as well as negotiate the turns needed to reach deep into the bundle. It was also necessary to devise some mechanical means of precisely positioning this band, or flex-lance, so that the operator would know the exact location of its tip and be able to direct it to specific areas. In addition to the water jets, the flex-lance could house a miniature video camera to allow the cleaning progress to be observed and to inspect conditions inside the tube bundle.

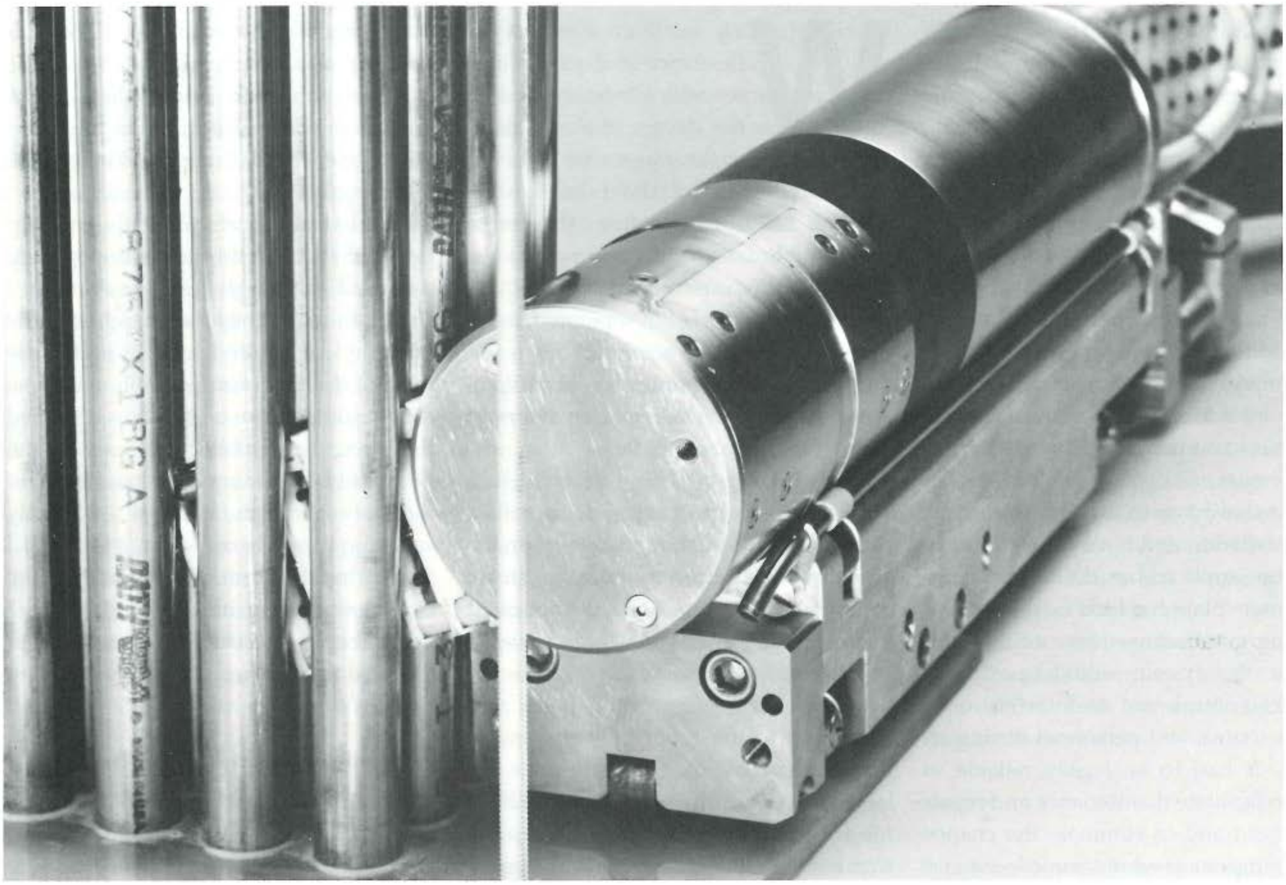
Armed with the raw concept of a flex-lance and some type of mechanical delivery system, Foster-Miller engineers set out to meet the design criteria established

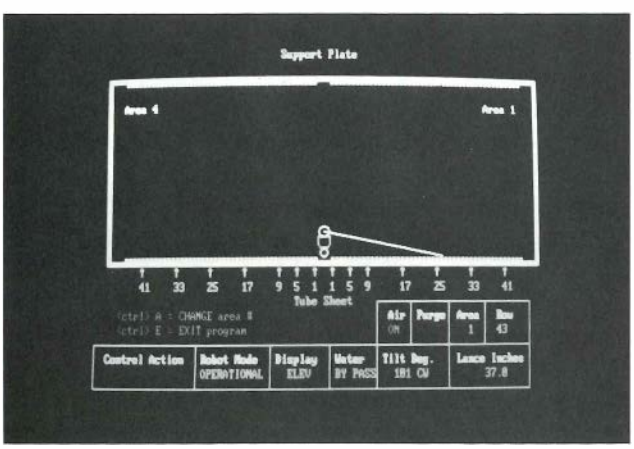


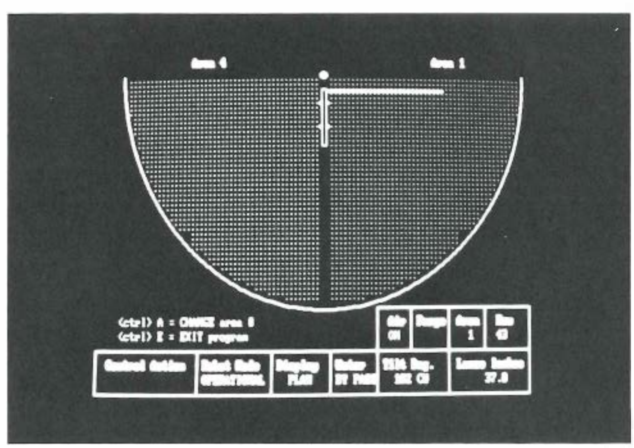
Steam generator

CECIL in Action

The large steam generators in PWR power plants are vulnerable to corrosion from sludge that accumulates near the vessel's base. The sludge often settles in a hardened mass deep within the tube bundle, where tight spacing and radiation limit human access for inspection and maintenance. Traveling between the legs of the U-tube assembly, CECIL extends its flex-lance deep into the tube bundle and sprays the sludge at close range with high-pressure water jets. A monitor displays robot and lance position graphically at a remote control station, and CECIL's operator can view the procedure directly in a video image from the miniature camera mounted on the tip of the flex-lance.







by the sponsors. The flex-lance would carry water to blast sludge at close range. "Imagine washing mud from your driveway with a garden hose," says Williams. "You can squirt at it from 15 feet away, but if you stand 4 inches away you'll get a much better blast because you've got your jet closer to the target." The flex-lance would have to be strong and stiff enough to withstand high internal water pressures—several thousands of pounds per square inch—while being flexible enough to move controllably within the tube bundle. "A person can hold a fire hose at the nozzle and keep it under control," Williams points out, "but hold it 10 feet back from the nozzle and it whips around like an angry python."

In addition to the strength and flexibility requirement, other considerations had to be addressed. Foremost among these was to minimize radiation exposure to operators. The manipulation of the lance would have to be done remotely, and installation and removal procedures had to be simple and quick. Because a nuclear power plant has little extra space for any equipment not used for routine maintenance, the system would have to be compact enough not to interfere with other activities and personnel during an outage. It had to be highly reliable in order to facilitate maintenance and repair in the field and to eliminate the chance that a component would come loose and get lost inside the steam generator. Finally, the design had to be adaptable to performing other tasks besides lancing and inspection, such as collecting sludge samples for analysis.

Turning concept into hardware

The flexible lance—though simple in concept—proved to be the project's toughest technical challenge. The most difficult problem was designing, and reducing to hardware, a water-delivery system that was both strong and flexible. This requirement ruled out the initial concept of an all-plastic flex-lance, which would swell under the internal water pressure. Foster-Miller engineers opted to use flexible stainless steel conduits lined with Teflon and sheathed in an extruded band of polyethylene. Holes punched between the conduits would mesh with sprocket teeth in the mechanical driver.

With work on a prototype flex-lance under way, Foster-Miller next turned to the design of a manipulator to feed the flex-lance into and out of selected areas of the tube bundle. Pushing the flex-lance from the access port would make it difficult to guide the tip into specific intertube gaps. What was needed was a remotely operated robot that could shuttle accurately up and down the steam generator's central blowdown lane and insert the lance at a right angle into the tube bundle.

The initial design effort resulted in a box-like prototype that slid on rollers along the top of the horizontal pipe in the blowdown lane used to drain the steam generator. The robot housed pneumatic actuators for propulsion and to power a sprocket drive to insert and withdraw the flex-lance. A remote control panel was connected to the robot by a pneumatic umbilical cord. Testing the prototype in a laboratory mockup of a Westinghouse Model 44 steam generator (the type at Con Edison's Indian Point Unit 2) demonstrated that the system could feed the lance in and out of selected tube lanes.

With feasibility demonstrated, Foster-Miller redesigned the robot in a configuration that could withstand the environmental conditions and spatial constraints it would encounter in the field. The new version, designated CECIL-3, was of single-piece construction, so no assembly was required before installing it in the steam generator. CECIL-3's stainless-steel cylindrical body is 18 inches long and slightly less than 3½ inches in diameter. The cylinder can be rolled via a cogged rubber belt, allowing the extended lance to move up and down in the tube corridors and, by rotating 180 degrees, to reach into both legs of the U-tube assembly from the central blowdown lane. CECIL-3 is propelled by the breast-stroke motion of two sets of spherical feet that engage gaps between tubes on either side of the blowdown lane. To move forward, the front feet retract and a pneumatic cylinder pushes the rear feet back, advancing the robot exactly one tube column with each step. When CECIL reaches the desired position in the blowdown lane, all four feet extend to lock the robot in place.

Further trials conducted in the mockup revealed that the flex-lance as originally designed, although functional, wasn't strong enough. The holes punched in the polyethylene tended to tear under the force of the sprocket teeth. To overcome this weakness, Foster-Miller redesigned the lance to resemble a latticed belt; the two flexible water conduits pass perpendicularly through a series of evenly spaced pins made of Delrin, a very hard form of nylon. In this configuration, the Delrin pins are pushed and pulled by the spaces between the sprocket teeth rather than the teeth themselves, thus reducing stresses on the lance.

Fighting sludge in the shadows

At the tip of CECIL's flex-lance is a nozzle block containing an upper and a lower set of multidirectional spray orifices fed by the two water conduits. Mounted in the center of the block are a 6-mm-diameter video camera lens and a tiny nozzle that shoots a stream of compressed nitrogen at the lens to keep it clear of water droplets and debris.

The spray orifices are designed to remove sludge from all sides of the steam generator tubes as the flex-lance travels down a tube lane. This cannot be accomplished with conventional techniques, which spray from only one direction, because the tubes mask the sludge behind them in so-called shadow zones. Two of CECIL's spray orifices are aimed straight ahead to break up sludge in the intertube lane. Orifices aimed at 45-degree angles break up sludge around the tubes, and an orifice at 90 degrees removes sludge in the shadow zones between tube rows.

Foster-Miller engineers developed a second flex-lance to retrieve samples of hard sludge from inside the tube bundle. Retrieving a sample would allow an analysis to be made of its chemical and physical properties, and perhaps provide clues to the mechanisms of sludge deposition and to improving sludge removal. The sampling lance is equipped with a 6-mm-diameter diamond-tipped core drill driven at 2000 rpm by a flexible shaft running through the lance. The sampling head also includes a video probe to monitor drilling progress and a water feed to lubricate the drill.

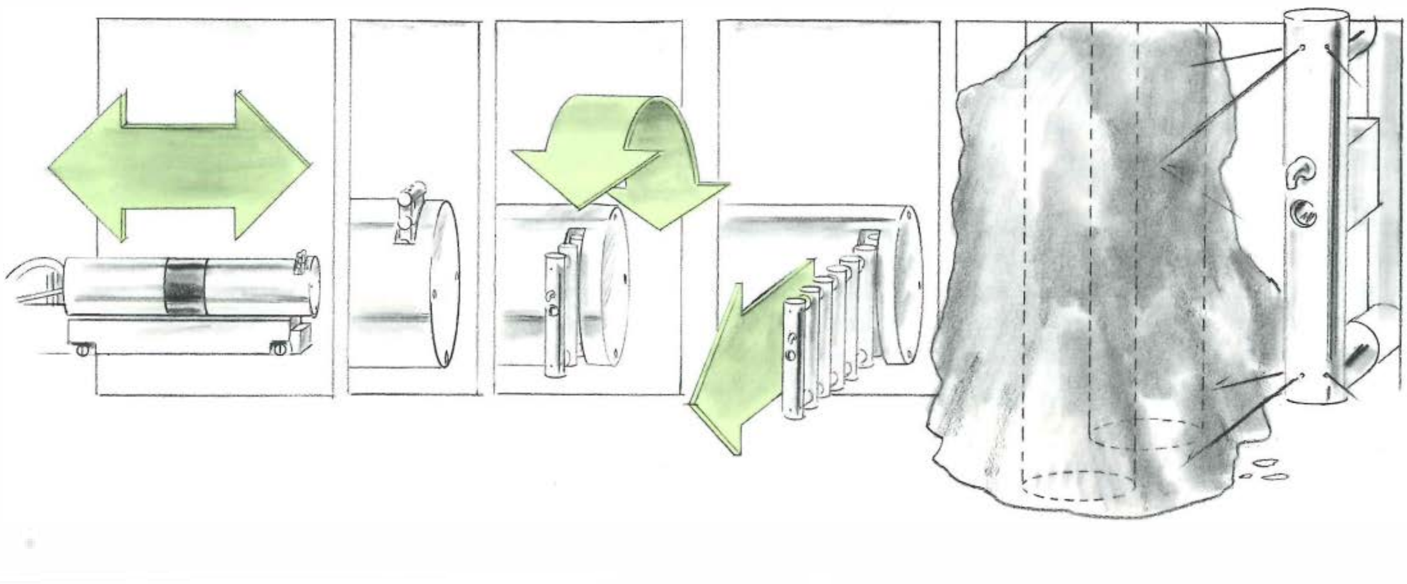
A computerized remote control and tracking system was developed to permit CECIL's operator to continuously monitor the positions of the robot and the flex-lance. CECIL's control station uses an IBM Industrial XT computer with the specifications of a Westinghouse Model 44 steam generator incorporated in software. Sensors inside the robot's body provide the operator with continuously updated information on the flex-lance's position. Potentiometers measure the motion of the flex-lance as it moves in and out of the tube bundle, as well as the angle at which the lance is deployed. The control computer processes these signals and displays them graphically on a monitor in either a plan or an elevation view of the steam generator. The graphics display tells the operator the quadrant being cleaned, the tube column in which the lance is located, the tube row in which the lance's nose is located, the extension of the lance (in inches) into the tube bundle, the angle at which the lance is tilted, and the operational status of CECIL and its support systems. The visual image from CECIL's camera is displayed on a separate video monitor, with flex-lance position data overlaid on the side of the screen. Coupling this monitor to a video cassette recorder makes it possible to create a permanent videotaped record of each sludge-lancing operation; such records can be reviewed to observe changes in steam generator conditions or to compare the effectiveness of successive sludge lancings.

To evaluate CECIL-3's ability to perform properly in the field, Foster-Miller put the robot through its paces in the laboratory mockup, trying to reflect as accurately as possible the conditions to be encountered in an actual steam generator. To do this, it was necessary to find an appropriate substitute for hard sludge. It's interesting to note—and indicative of the difficulty of reaching into a steam generator—that no data were available on the material properties of hard sludge. A poll of industry sources, research organizations, and universities indicated that a recipe of three parts Portland cement to one part magnetite—the iron oxide thought to be the primary constituent of steam generator sludge—would yield a suitable analog. Mixed with enough water to form a thick paste, this concoction was ladled into the steam generator mockup and allowed to set for intervals of eight hours to several days to attain various degrees of hardness.

In multiple tests using a nozzle pressure of 2500 psi, the system was able to erode the mock sludge at short distances, including sludge in the shadow zones between tubes. But as the range between the nozzle and the sludge pile increased to a foot or more—simulating conventional lancing—the spray failed to erode the material. Tests conducted with the

Robotic Inspection and Cleaning

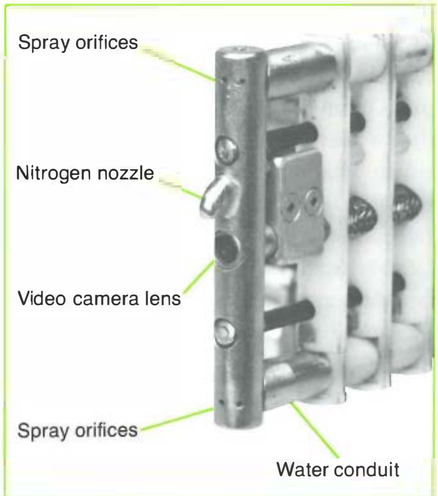
Propelled by pneumatically actuated feet, CECIL shuttles up and down the steam generator's central blowdown lane and inserts its flex-lance into the tube bundle. A motor in CECIL's base and a drive belt rotate the robot's cylindrical body, allowing the flex-lance to deal with varying sludge pile heights and to reach into both sides of the tube bundle from the blowdown lane. The flex-lance's multidirectional sprays are designed to remove sludge from all sides of the tubes, and the lance-mounted video camera allows the operator to inspect tube bundle conditions.



Water Lancing and Core Drilling

The business end of CECIL's flex-lance is a marvel of miniaturization. Upper and lower sets of multidirectional spray orifices are fed by two water conduits that run through the flex-lance. A 6-mm video camera lens mounted in the center of the block allows CECIL's operator to observe progress, while a tiny curved nozzle shoots a stream of compressed nitrogen at the lens to keep it clear of mist and debris.

A separate drilling head, also video equipped, is used to collect core samples of sludge for chemical and physical analysis. The diamond-tipped core drill is driven by a flexible shaft built into the lance parallel to the water conduits.



sampling lance showed that the diamond-tipped drill was able to successfully penetrate the simulated sludge and retrieve core samples.

A major concern in the project was that CECIL's high-pressure sprays might erode or cut the nickel-alloy tubes—in fact, high-pressure water jets are used specifically to cut steel in other industrial applications. Foster-Miller conducted a series of tests to determine tube erosion as a function of water pressure, standoff distance, and exposure time. These tests revealed that the maximum tube erosion occurred when the distance between the nozzle and the tubes was from 3 to 9 inches. The reason is that air becomes entrained in the water about 3 inches from the nozzle, increasing the jet's cutting action; past 9 inches, the jet disperses and loses energy. In operation, CECIL would be lancing at a range of just 1½ inches. By the time the jets reached the critical 3–9-inch distance, all the sprays would be splattering off the tubes, resulting in imperceptible damage.

Another concern that had to be addressed before testing CECIL in the field was its ability to operate under abnormal conditions. The worst-case scenario was considered to be a simultaneous loss of all electric and pneumatic power. With electric power cut off, CECIL's control computer—and the operator—would lose track of the robot's position inside the steam generator. And without pneumatic power, CECIL could not withdraw the flex-lance or walk out of the generator. Foster-Miller provided a backup battery to ensure a continuous supply of power to the computer, and decided to use compressed nitrogen instead of air to power CECIL's pneumatic actuators. Compressed nitrogen would allow the robot to operate independently of power plant compressed-air systems. Foster-Miller also fitted a shear pin into CECIL's drive sprockets so that a tug on the flex-lance outside the steam generator would break the pin and allow the sprockets to freewheel. With this arrangement the robot and flex-lance could still be manually retrieved in the unlikely event that pressure was lost or if the lance became snagged inside the tube bundle.

Demonstration at Indian Point

As the October 1987 refueling outage at Con Edison's Indian Point Unit 2 approached, Foster-Miller added final refinements to prepare CECIL for its first field demonstration. The most important of these was a means of getting the robot in and out of the steam generator while keeping radiation exposure as low as reasonably achievable. Foster-Miller designed an installation ramp the same diameter as the steam generator's blowdown pipe. The ramp and robot are inserted into the inspection port and tilted, and CECIL slides gently onto the blowdown pipe. The entire installation sequence takes less than a minute.

For the demonstration, CECIL's nitrogen supply, water pumps, and trailer-mounted water tanks were set up outside the plant's containment. The control station was set up on the operating floor inside the containment, in a low-radiation area about 75 feet from the steam generator. A take-up reel was mounted on the generator's inspection port to prevent CECIL's umbilical and flex-lance from tangling inside the generator. With all systems in place, CECIL was lowered into the steam generator to inspect, lance, and sample under real-world conditions.

The demonstration was conducted immediately after a conventional sludge-lancing procedure. CECIL's camera revealed that several rows of tubes close to the blowdown lane were clean, but as the lance advanced a short distance into the tube bundle the video showed sludge coating the tube walls. Less than 9 inches into the tube bundle, the lance encountered a wall of hard sludge that completely filled the intertube gap. Inspection of other tube lanes revealed a large sludge pile on the tubesheet, rising in height toward the interior of the tube bundle.

"The sharpness and clarity of the video were just incredible," says Stephen Trovato, a senior research engineer at Con Edison who managed the project for the utility. "The robot took the camera in upright and went down individual tube lanes and took superb pictures. It's the finest inspection footage ever taken inside a steam generator."

Having passed the inspection test with extremely successful results, CECIL next took on the task of lancing the hard sludge left behind after conventional lancing. The solidified mass proved to be far more tenacious than originally believed—much harder than the cement-based mixtures used in the laboratory mockup. With CECIL's nozzle delivering 2500 psi of spray energy, the water jets could only slowly erode the thick sludge pile on the tubesheet. The limited outage time available for field-testing CECIL permitted only one attempt at retrieving a sludge sample with the drilling lance. Spinning at 2000 rpm, the core drill successfully cut into the sludge, but it failed to retrieve the sample. "The core sample may not have snapped off at its root," says Trovato. "We're looking at a redesigned sampling lance that may solve the problem. We also think we can improve sludge removal by lancing at higher pressures."

Overall, CECIL's first demonstration at Indian Point 2 provided encouraging results. The system successfully demonstrated its ability to conduct detailed inspections in the tube bundle, and with further refinement, it may prove effective for hard-sludge removal and sludge sampling. The field trial also proved that these tasks can be remotely controlled and monitored to minimize the operator's exposure to radiation.

"I think the biggest challenge in this program was the time constraint," says Trovato. "We went from a concept sketch of a flexible lance—a sketch, not an engineering drawing—to the device that was used in the plant in only nine months, complete with support systems."

Improving CECIL

Although EPRI's participation in the program extended only up to the demonstration of CECIL-3 at Indian Point, Foster-Miller has been continuing development under sponsorship from Con Edison, ESEERCO, Public Service Electric & Gas, and Northern States Power. Building on the lessons learned during the first field test, Foster-Miller engineers have developed a new version of the robot, designated CECIL-4. The new version is smaller, faster, and more powerful, and it has expanded capabilities.

Locomotion and power are provided by electric motors instead of pneumatic actuators, and a proportional control system will enable the operator to vary the speed with joysticks. The flex-lance has been redesigned to carry four water conduits instead of two, and the spray-jet orifices have been refined to operate at 7500 psi instead of the 2500 psi of the earlier version. CECIL-4's mode of locomotion is also different. Instead of crawling down the blowdown pipe, the robot will travel into the steam generator suspended from a horizontal rail installed through the steam generator inspection port. With this arrangement the lance's progress into the tube bundle will not be blocked by sludge deposits, and the higher elevation will permit the operator to look down on the sludge pile to get an overview of the extent of sludge deposition before beginning lancing. The suspended-rail approach will also extend CECIL's adaptability to all Westinghouse Model 44 and Model 51 steam generators. Foster-Miller is also adding high-volume spray nozzles to the robot body itself. This feature will allow it to perform conventional soft-sludge lancing from the blowdown lane in addition to the other tasks—all in one remotely controlled package. CECIL-4 will get an opportunity to demonstrate these refinements this spring during scheduled outages at Indian Point 2 and at PSE&G's Salem Unit 1.

Through an agreement with EPRI, Con Edison, and ESEERCO, Foster-Miller is licensed to commercialize CECIL technology. The company is also working to adapt CECIL to different steam generator designs and to apply the technology to other applications that require accurate and repeatable access to hard-to-reach locations.

"When we started this project we didn't want to develop something that competes with existing practices," says EPRI's Williams. "Our goal was to develop a tool to perform tasks that couldn't be done with existing methods—getting inside the tube bundle to make a good visual inspection and removing the hard sludge that conventional techniques don't remove. CECIL will give utilities important information on steam generator conditions so they can make decisions relating to maintenance and reliability. They can't make those decisions unless they know what's inside the steam generator, and with CECIL, they can. People have peeked through the door, but CECIL has opened it." ■

Further reading

CECIL: A Robot for Secondary-Side Maintenance of PWR Steam Generators. Final report for RPS403-3, prepared by Foster-Miller Inc., February 1989. EPRI NP-5929.

CECIL—A Robot for Secondary-Side Steam Generator Maintenance. May 1988. EPRI Videotape NP88-01.

NDE and Mechanical Removal of Sludge in PWR Steam Generators, Vol. 1: Overview and Utility Experiences. Final report for RPS403-2 and RP2755-2 and -6, prepared by Dominion Engineering, Inc., and LN Technologies Corp., January 1988. EPRI NP-5563.

NDE and Mechanical Removal of Sludge in PWR Steam Generators, Vol. 2: Vendor Practices. Final report for RPS403-4 and RP2755-3 to -11, prepared by ANCO Engineers, Inc., Babcock & Wilcox Co., Combustion Engineering, Inc., Foster-Miller, Inc., and Westinghouse Electric Corp., January 1988. EPRI NP-5563.

This article was written by David Boutacoff. Technical background was provided by C. Lamar Williams, Nuclear Power Division; Stephen Trovato, Consolidated Edison; and Steven Ruggieri, Foster-Miller, Inc.

TECH TRANSFER NEWS

Technologies Work at Utilities

EPRI publications, seminars, and workshops on new and emerging technologies, research data, and methodologies are often seen as the first step in the process of technology transfer. But however efficient EPRI may be in responding to utility requests for technical help and information, real technology transfer begins when a utility puts these products to work—when it takes the plunge to become a first or early user of technology that previously has only been talked about.

This pioneering of innovation by utilities is the most important step in the process of technology transfer. To make it work, a utility must have management that appreciates the value of R&D, a commitment to applying new or improved technology, and resources to back up this commitment. Most important, it must advance a corporate philosophy that cultivates "product champions"—individual employees who make personal efforts to see the application of a new technology through to completion. The commitment can pay off in millions of dollars of savings for the utility.

Such savings are formally documented in EPRI's *First Use* information sheets, each of which describes the use of an EPRI product to solve a utility problem and quantifies the resulting benefits, as calculated by the utility itself. In the spring of 1988, EPRI President Richard Balzhiser set a goal of formally documenting 40 first or early uses of the Institute's technology over the calendar year, with a total utility savings of at least $300 million. As the table below illustrates, the actual number was 45 by the year's end, with savings reported by the utilities involved of almost $690 million—more than double the targeted goal.

Utility	Application	Levelized Annual Savings ($000)	Total Estimated Savings ($000)
Alabama Power Co.	Heat pump service life and maintenance characteristics (FS8443A)*		8,715
Boston Edison Co.	Low-loss PPP-insulated cable installation (FS8103C)	720	5,865
Commonwealth Edison Co.	Seismic qualification at older nuclear plants (FS8433B)	10,800	60,000
Consolidated Edison Co. of New York	Chemistry control for PWR primary coolant system (FS8213B)	275	661
Consolidated Edison Co. of New York	Boiler stress and condition analyzer (FS8316B)	659	5,921
Consolidated Edison Co. of New York	Remote robotics for PWR steam generator inspection/maintenance (FS8319B)	657	657
Duke Power Co.	Rotor remaining life analysis (FS8210B)	2,298	12,984
Duke Power Co.	Steam generator chemical cleaning qualification; corrosion monitoring system design/construction (FS8315B)	7,697	7,697
Duke Power Co.	Liquid radwaste pretreatment (FS8426B)	1,414	7,679
Duquesne Light Co.	Pipe whip restraint reduction (FS8211B)	1,126	1,126
Florida Power Corp.	Fault tree analysis (FS8212B)	51	183
Florida Power Corp.	Gas turbine performance analysis (FS8438B)	50	50
General Public Utilities Nuclear Corp.	Rotor crack detection in pump maintenance (FS8107B)	748	3,793
Georgia Power Co.	LOCA licensing requirements for BWRs (FS8321B)	702	3,513
Georgia Power Co.	Weld overlay NDE (FS8424B)	135,000	135,000

Utility	Application	Levelized Annual Savings ($000)	Total Estimated Savings ($000)
Houston Lighting & Power Co.	High-voltage instrument transformer testing (FS8434C)	104	181
Iowa-Illinois Gas and Electric Co.	Transmission svstem reliability analysis (FS8429C)	20	20
Los Angeles Dept. of Water & Power	HVDC subsynchronous oscillation analysis (FS8314B/C)	10,296	10,296
Mississippi Power & Light Co. (Grand Gulf Nuclear Station)	Precoat filtration of BWR floor drain wastes (FS8106B)	1,566	8,668
New England Electric System	Interruptible/curtailable rate design (FS8439A/E)	112	112
New England Power Service Co.	HVDC control modeling (FS8428C)	55	221
New York Power Authority	Radiation field reduction in steam generator tubing (FS8322B)	805	7,900
New York State Electric & Gas Corp. and Pennsylvania Electric Co.	Heavy media cyclone performance analysis (FS8209B)	80	140
New York State Electric & Gas Corp.	Wet-stack systems analysis (FS8435B)	8,399	52,127
Niagara Mohawk Power Corp.	BWR Repair Applications Center IGSCC assistance (FS8427B)	13,678	13,678
Northeast Utilities	Tests of coatings for insulator surfaces (FS8101B)	317	1,829
Omaha Public Power District	Wood pole strength analysis (FS8104C)	79	567
Pacific Gas and Electric Co.	Automated remote vibration monitoring (FS8431B)	1,553	8,960
Pacific Gas and Electric Co.	Instream flow guidelines (FS8441B/E)	412	2,377
Pennsylvania Electric Co.	High-frequency axial fan vibration monitoring (FS8425B)	245	1,505
Public Service Co. of Indiana	FGD system sulfur treatment (FS8430B)	546	3,955
Public Service Electric & Gas Co.	Stability analysis after a major disturbance (FS8442C)	300	300
Rochester Gas & Electric Corp.	Rotor remaining life analysis (FS8318B)	1,000	1,000
Southern California Edison Co.	Structural integrity analysis following transient (FS8423B)	100	100
Southern California Edison Co.	Automated on-line fatigue monitoring (FS8436B)	165	165
Union Electric Co.	Underground storage tank replacement analysis (FS8437B/C/E)	172	1,260
Utah Power & Light Co.	Process chemistry in FGD system analysis (FS8102B)	485	3,908
Utility Solid Waste Activities Group	PCB cleanup risk analysis (FS8440B/C/E)	51,427	216,044
Vermont Yankee Nuclear Power Corp.	BWR radiation control program (FS8320B)	549	4,101
Virginia Power	FGD cost-estimating guidelines (FS8208B)	100	100
Virginia Power	Dry storage of spent fuel in metal casks (FS8317B)	11,575	90,101
Virginia Power	Amorphous metal core transformer installation (FS8445C)	128	946
Wisconsin Electric Power Co.	Disposal site/groundwater quality impact analysis (FS8432B/E/F)	80	80
Yankee Atomic Electric Co.	Computerized display system for nuclear control room operators (FS8105B)	2,740	2,740
Yankee Atomic Electric Co.	BWR LOCA analyses (FS8444B)	584	2,665
		Total	689,890

**First Use* document number. *First Use* sheets can be ordered from EPRI, P.O. Box 23205, Pleasant Hill, CA 94523, (415) 934-4212.

Power Electronics Applications

End-Use Power Quality

by Marek Samotyj, Customer Systems Division

ABSTRACT *Electric utilities are taking steps to turn the emerging electric power quality problem into an opportunity by providing demand-side power-conditioning equipment, applications engineering and expertise, and consulting services to meet customer needs. The increased sensitivity and proliferation of end-use loads brought on by the microelectronics revolution have led to a market for uninterruptible power supplies and power-conditioning systems. In response, EPRI has initiated scoping studies to furnish a discussion of issues relevant to power quality.*

The main objectives of EPRI's scoping studies were to define power quality (PQ) and identify essential technical elements and their relationships. The studies also set out to identify methodologies for assessing power quality and to recommend improvements; to distinguish the benefits and limitations of mitigation systems; and, finally, to outline research needs.

Elements of power quality

The existing standard for PQ (ANSI C84.1) specifies that steady-state voltage tolerances for an electric utility at the point of service be within 5% for nonlighting loads. The standard also specifies the steady-state voltage tolerances at the point of utilization. Equipment using electricity should be designed to give satisfactory performance throughout the range of +4% to −10% and acceptable performance in the range of +6% to −13%. However, the specification of steady-state voltage limits is in many ways insufficient, given the state of today's microelectronics technology. What constitutes acceptable performance and acceptable PQ in the case of computers that process millions of bits of information using low-voltage logic is more difficult to define.

The ANSI standard is a good starting point, but it addresses only two types of power disturbances (steady-state voltage minimums and maximums) out of the eight or more types that occur on electric distribution systems. Power disturbances include:

- Power failures—long-term blackouts that last more than a few minutes, and short-term outages that last less than a few minutes
- Voltage sags and surges—short-term, transient conditions and long-term, steady-state voltage-regulation problems
- Waveform distortions—continuous, repetitive harmonic distortions and occasional glitches or notches in the waveform
- Flicker—repetitive sags and surges in the voltage, often accompanied by nonperiodic harmonic distortions
- Voltage spikes—high-voltage transients, usually induced by lightning
- Electrical noise—random, low-level static

A comprehensive definition of PQ would take into account the many types of power disturbances that occur and would define limits with parameters appropriate to each type in terms of deviation from a perfect 60-cycle voltage sine wave. PQ has not yet been defined in these terms, however, partly because of the relatively recent emergence and proliferation of sensitive loads and partly because of the difficulty associated with quantifying the costs of poor PQ.

The point-of-service and point-of-utilization distinctions in the ANSI standard are useful concepts, but because an electric power distribution system interconnects many types of loads, many disturbances pass from one customer to another and cannot be easily controlled by the utility. Also, disturbances that are perceived by the customer as utility PQ problems are often created by improper wiring within the customer's own facility.

Mitigation systems

Delivering a superior grade of electricity does not involve rebuilding a utility's distribution infrastructure. Rather, it is similar to providing conditioned phone circuits for computer communications in the telecommunications industry, where, in order to enhance the existing phone network, standard voice-grade channels are combined and equalized by interface equipment. Power-conditioning equipment is similarly employed at the point of customer use to enhance the quality of power provided by the utility.

The systems approach to PQ assurance takes into account the interconnectedness of the distribution system, wiring features on the customer's premises, measures aimed at reducing interference, and measures aimed at mitigating power disturbances. Mitigation measures include transient voltage suppressors, voltage regulators, isolation transformers, motor-generators, power line conditioners, uninterruptible power supplies, and other types of power-conditioning equipment.

Electric utilities for many years have devoted resources to supply-side PQ, including measures to control power disturbances associated with generation (harmonic filters), transmission (lightning arrestors), and distribution (lightning arrestors, delta-wye-connected transformers, power-factor-correction capacitors, static VAR compensators). Control measures continue to be appropriate. However, because not all sources of interference are likely to be known to the utility, it may be more practical to devise and implement measures to mitigate the effects of power disturbances, regardless of their source.

The "hardening" of susceptible loads involves incorporating selected mitigation measures into the susceptible-load power supply. Examples are alarm clocks and video cassette recorders that incorporate battery backup to protect the timekeeping function from short-duration outages. Other types of hardening are software measures used in the operating systems of computers: for example, computer programs that store data in nonvolatile media when a power outage is sensed.

End-user perspective

Electric utilities are ideally situated to meet the challenge of PQ assurance because their perspective is, by nature, a systems one. The costs of control at the source end and the costs of effects mitigation at the receiving end can be jointly minimized by a systems perspective. The first set of costs is directly under the control of the utility, depending on the structure and scope of the PQ assurance program.

Although the utility's role can be that of consultant in this regard, it falls to end users of critical loads to face the dilemma of weighing the costs of mitigation against the costs of susceptible-load failure. Whether or not the user buys power-conditioning equipment (and thus a superior grade of electricity), the probability of power disturbances of a certain magnitude per year remains the same. If the customer has elected to buy power-conditioning equipment, there is still the finite probability that the protection equipment itself will fail.

Thus, the end user's problem is to weigh the costs, in the absence of mitigation equipment, of power disturbances of various magnitudes against the costs of the same disturbances with mitigation equipment. Losses are expected to be reduced in the latter case, but the annualized cost of the mitigation equipment must be taken into account.

End-use R&D plan

Power quality from the perspective of electricity customers has many ramifications for electric utilities. End-use PQ involves issues such as customer relations, dealing with equipment vendors, power monitoring, establishing specifications for power-conditioning equipment, and power requirements. In an effort to help electric utilities understand and address this challenge, EPRI held two R&D planning sessions in 1987 and one in 1988.

The first meeting brought together a group of experts from industry, academia, and electric utilities in a planning session on end-use power quality. The objective of this meeting was to discuss the key issues of end-use PQ and to identify and define R&D goals that must be established to monitor, measure, and improve the quality of power reaching utility customers.

The second meeting presented an opportunity for electric utilities to review the results of the previous meeting. Representatives from utilities, power-conditioning manufacturers, universities, and EPRI's Power Electronics Applications Center (PEAC) provided input during these R&D planning sessions. Based on the workshops' recommended short- and long-term R&D projects, a list of six generic activities to be undertaken by EPRI and PEAC was developed. Each specific project undertaken by EPRI and PEAC should focus on one or more of these activities:

- Determine the factors that define PQ requirements and problems for end users
- Survey existing techniques and equipment that are used to monitor, measure, and correct problems
- Conduct field tests of existing and advanced power-conditioning equipment at industrial sites to determine the extent to which disturbances and distortions are either mitigated or exacerbated
- Collect and analyze utility data related to power quality
- Develop cost-benefit analyses of corrective measures for all sectors, with initial emphasis on industrial customers
- Investigate business opportunities for electric utilities to provide corrective equipment and measures

The suggested topics for research studies developed during the workshops have been redefined as necessary to eliminate duplication of effort and to improve efficiency. In October 1988, during the final R&D planning session, these revised topics were discussed and ranked within three major areas of an end-use R&D plan: knowledge-base development and transfer, methodologies for PQ assessment and improvement, and research and equipment development. At the same time the Power Quality R&D Plan was published (EM-6109).

The recommended research will flow through a sequence of stages: survey, evaluation, initial technology transfer, systems, applications, and subsequent technology transfer. Several of the proposed projects are now under way, primarily in the knowledge-base development area. Information on mitigation equipment, including pertinent definitions and specifications, is being assembled. PQ terms are being defined in order to establish the shared working vocabulary necessary for a successful collaborative program. Seminars and workshops are being arranged, the most recent being the National Conference on Power Quality for End-Use Applications, held in San Antonio, Texas, during March 1988.

This conference, which was accompanied by an exhibition of power-conditioning equipment, was the first national gathering of representatives from all three parties interested in end-use PQ—utilities, end users, and equipment manufacturers. EPRI and PEAC staff have been cooperating closely with IEEE working groups to improve methodologies for measuring PQ, develop a utility test code for power-conditioning units, and set standards. On the research side, available methods for active power line conditioning, intelligent harmonic filtering, and other mitigation techniques are being analyzed.

The research plan will be managed and coordinated through EPRI's Power Electronics and Controls Program, using PEAC's Power Quality Laboratory and Power Quality Educational Services. EPRI will identify factors contributing to improved power quality; quantify the effect of PQ factors on various system components and loads; assess the cost of each type of power disturbance (e.g., sags, surges, harmonics, transients); and identify solutions for each of these problems. PEAC's role will be to assess the cost and effectiveness of each solution method through laboratory and field testing, while EPRI completes a cost-benefit analysis for improved PQ.

EPRI will issue R&D prospectuses for several PQ equipment demonstration projects to be developed on a collaborative basis with industry cost sharing. As the research program is implemented, new opportunities for future R&D will arise, and the boundaries of the current effort will expand. EPRI will closely coordinate implementation of this research plan with international research efforts. Feedback, especially from end users, will continue to be a key factor.

Fossil Power Plants

Improving Electrostatic Precipitator Performance

by Ralph Altman, Generation and Storage Division

ABSTRACT *The performance and reliability of electrostatic precipitators, the predominant particulate control method for coal-fired boilers, are increasingly affecting power plant performance as the ESP population ages. Four technologies—wide plate spacing, intermittent energization, flue gas conditioning, and two-stage precipitation—show potential for restoring ESP effectiveness while reducing both capital and operating costs.*

Most U.S. coal-fired utility boilers use electrostatic precipitators (ESPs) for particulate control. Although ESPs are relatively simple and reliable devices, many utilities experience performance problems as a result of undersized units, deterioration of aging equipment (over 20% of existing precipitators are more than 25 years old), or switching to a coal that produces a difficult-to-collect fly ash.

EPRI has conducted a number of research projects to address these performance and reliability problems. The technologies under investigation, which can all be retrofit to existing units, include wide plate spacing, intermittent energization (IE), flue gas conditioning, and two-stage precipitation. They have been tested in the laboratory and at pilot scale; two of them, IE and wide plate spacing, have been successfully applied to full-scale units.

The EPRI studies have made the following findings:

- Intermittent energization can reduce energy consumption and in some applications improve collection efficiency.
- Wide plate spacing can reduce the capital cost of a new precipitator and the cost of rebuilding an existing unit.
- Both conversion to two-stage operation and the use of flue gas conditioning can improve collection efficiency for high-resistivity fly ash.

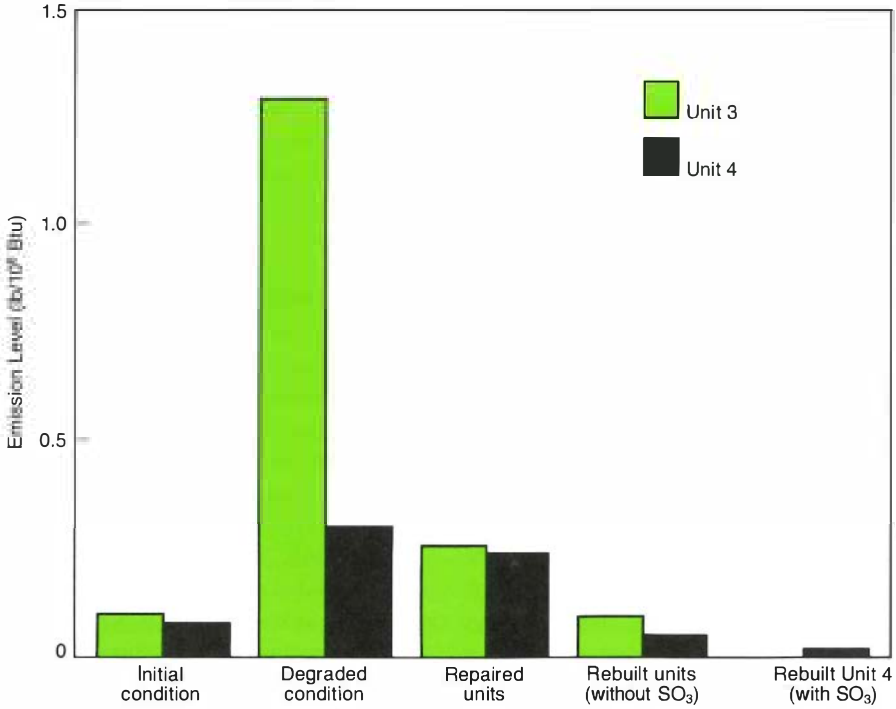
Wide plate spacing

Most precipitators at U.S. power plants space the collection electrodes 9 inches apart, but newer installations in Europe use spacings of up to 16 inches. To determine the allowable spacings for U.S. applications, EPRI modified a 1-MWe (equivalent) pilot precipitator at Public Service Co. of Colorado's Arapahoe station so that the plate spacing could be varied. Tests conducted by Combustion Engineering and Southern Research Institute using this pilot unit demonstrated that the spacing could be increased to 18 inches with no loss in performance, even though the collection area of the precipitator would be reduced by as much as one-half.

Results from Arapahoe helped engineers at East Kentucky Power Cooperative decide to increase plate spacing when rebuilding two ESPs at the Dale station (Units 3 and 4) in 1987. These two 66-MW boilers, originally equipped with mechanical collectors for fly ash control, were retrofit with cold-side, weighted-wire ESPs with 9-inch plate spacings in 1975.

When the precipitators were rebuilt in 1987 in response to chronic performance and reliability problems, the weighted-wire discharge electrodes were replaced with rigid discharge electrodes, a step that required widening the plate spacing from 9 to 12 inches. Since the existing casings were retained in the rebuild, this change decreased the specific collection area (SCA) from 400 to 300 ft²/1000 acfm. However, the performance of the ESPs actually improved (Figure 1), while the cost of the rebuild was reduced by an estimated 12%.

Figure 1 Performance histories of Dale station ESPs from installation through rebuilding. The two left-hand pairs of bars illustrate the deterioration in performance experienced one to three years after startup. Installing an SO_3 conditioning system and performing mechanical repairs improved performance, but continued high maintenance costs prompted East Kentucky Power Cooperative to rebuild the internals of both units. Rebuilding significantly lowered emission levels without SO_3 conditioning; using SO_3 conditioning with the rebuilt Unit 4 lowered emission levels to 0.02 lb/10^6 Btu.



Intermittent energization

IE, also in the full-scale demonstration phase of testing, is a method of modifying the voltage and current waveforms used to energize electrostatic precipitators by blocking selected half-cycles of power to the transformer-rectifier sets. Each precipitator acts as a capacitor during the deenergized period, and, as a consequence, the time-averaged field strength within the precipitator can be almost as high as it is when conventional energization is used.

The effect of IE on precipitator performance depends on the nature of the fly ash being collected. If the dust has a high resistivity, as does the dust produced by low-sulfur coal, and the precipitator is operating in back corona, IE can actually improve performance because reducing the current in the precipitator reduces the degree of back corona. This improvement in performance will be accompanied by a reduction in energy consumption of 50% or more.

With a moderate- or low-resistivity fly ash (i.e., medium- or high-sulfur coal), it is usually possible to halve energy consumption, but in this case there will be no improvement in performance or reduction in opacity. The same result (reduced power consumption with no improvement in performance) is obtained if the precipitator is collecting high-resistivity dust that does not produce back corona, a condition that sometimes occurs for reasons that are not fully understood.

There are certain low- and moderate-resistivity applications, however, that do not produce favorable results. These occur when the precipitator has a very high superficial gas velocity or the fly ash has an extremely low resistivity. In the former case IE may exacerbate rapping losses, particularly in the last field of the precipitator, while in the latter case IE may increase both continuous and rapping reentrainment losses.

Full-scale tests of IE at Consumer Power's Campbell Unit 3 confirmed the pilot-scale results. IE reduced ESP power consumption by approximately 50% on a precipitator that was collecting fly ash with a moderate resistivity. In another application, a hot-side precipitator at Mississippi Power's Plant Daniel was recently retrofit with IE controls. Comparative tests were conducted to establish the effects of IE controls on both precipitator performance and power consumption. At full load on the boiler, IE reduced power consumption 32% with no deterioration of emission control. In fact, the measured discharges actually decreased by slightly over 10%.

Two-stage precipitation

Tests of a new two-stage precipitator have been completed through the large-scale pilot stage. Two-stage precipitation separates the charging and collection functions of a precipitator by precharging fly ash prior to collection. This practice makes the collection efficiency of a precipitator almost independent of fly ash resistivity (i.e., coal sulfur content). This technology should provide a lower-cost alternative to flue gas conditioning, the method currently used to lower fly ash resistivity when low-sulfur coals are burned.

Although the concept of precharging is an old one, only recently has a practical precharger been developed. With this cooled-pipe precharger, relatively high electrical fields and current densities can be achieved, and highly charged particles are produced regardless of the resistivity of the fly ash.

This concept, conceived by University of Denver researchers under the sponsorship of the U.S. Environmental Protection Agency, has recently been tested by EPRI using a 5-MWe pilot-scale precipitator at Public Service Co. of Colorado's Valmont station. The low-sulfur western subbituminous coal burned at Valmont produces fly ash of high resistivity. As a result, the performance of the precipitator without precharging was only a little over 90%. Energizing the prechargers dramatically improved performance: with all four prechargers energized, the collection efficiency increased to 99%, a high collection efficiency for a precipitator operating with an SCA of only 200 $ft^2/1000$ acfm.

Precharging could increase collection efficiency to levels attainable with SO_3 conditioning, but at approximately half the capital cost. Further, operating costs should be reduced, since no reagent is needed. EPRI is seeking a host utility for a full-scale test of the two-stage precipitation concept.

Flue gas conditioning

As noted earlier, conditioning flue gas with SO_3 is the traditional method for improving ESP performance when low- or medium-sulfur coal is burned. Conventional SO_3 conditioning systems are costly, however, so EPRI is working to develop a simple, inexpensive, and reliable alternative. The most promising concept involves a catalyst in a duct bypassing the economizer that oxidizes SO_2 in the flue gas to SO_3. Approximately 1–3% of the flue gas would be directed through the duct and over the catalyst before being reinjected into the bulk of the flue gas following the air heater. Thus the requisite SO_3 would be generated from the SO_2 that occurs naturally in the flue gas, with no need to buy sulfur reagent or operate external process equipment.

Unfortunately, no catalyst with the necessary physical and chemical properties is commercially available. EPRI is now working with SRI International and Southern Research Institute to develop such a catalyst. Preliminary tests of several candidates have yielded encouraging results, with SO_2-to-SO_3 conversion efficiencies greater than 90% in reasonable-sized reactors (residence times approximately 0.1 second). If the laboratory results continue to show promise, EPRI will begin looking for a plant site for pilot-scale tests in mid-1989 to verify catalyst lifetimes.

This flue gas conditioning system is estimated to be less expensive than conventional systems and can be used in those cases where space constraints within the precipitator would make conversion to two-stage operation difficult.

In summary, these four technologies can reduce the capital and operating costs and improve the reliability of precipitators. Furthermore, conversion to two-stage operation or to the flue gas conditioning system under development could greatly reduce the sensitivity of precipitator performance to the sulfur content of the coal supply. This last capability is particularly significant for those utilities who may want to switch to low-sulfur coal in order to take advantage of lower market prices or to comply with any acid rain legislation that is enacted.

In addition to completing the development and demonstration of these ESP upgrades, future work will assess the effects of new SO_2 control systems—spray drying, dry sorbent injection, and conversion to fluidized-bed combustion—on electrostatic precipitator performance.

Utility Planning

Industrial Demand-Side Management Applications

by Paul Meagher, Customer Systems Division

EPRI's industrial demand-side management applications (IDSMA) project has been designed to demonstrate approaches that will help utilities plan and implement industrial DSM. It builds on the DSM planning process that EPRI has developed for use by utilities and represents a real-world testing ground for various industrial DSM strategies.

The industrial sector is an ideal setting for demand-side management. Industrial facilities have relatively high demands for electricity compared with residential and commercial customers. Accordingly, industrial DSM measures can be more cost-effective than similar measures in the other sectors. In addition, because many industrial facilities operate around the clock, greater flexibility exists in schedule modifications; this can be an important advantage in designing a DSM strategy.

Despite the potential advantages of industrial DSM, relatively little work has been undertaken in this sector compared with the residential and commercial sectors because of the greater difficulties involved in implementing industrial DSM. Industrial uses of energy are highly diverse. Often two facilities produce the same product with similar processes but differ in significant ways. These differences require that analyses of DSM potential be undertaken case by case. In addition, utility expertise in how industrial customers use energy is generally limited. Finally, there are relatively few demonstrations of industrial DSM that can serve as models for future efforts.

IDSMA case studies

The IDSMA project is helping to point out ways that utilities can overcome these problems. It employs a case study format in which a utility goes through the entire DSM planning and implementation cycle for its industrial sector. For each utility, this process includes defining its DSM goals, segmenting its industrial market, investigating manufacturing operations and energy use, creating marketable DSM products, and initiating DSM demonstrations at industrial facilities. The intent of these case study efforts is to explore how utilities can work cooperatively with their industrial customers to produce benefits for both parties.

The first step in each case study has been to define the utility's underlying objectives in implementing DSM. These objectives often combine a number of factors, such as financial considerations, customer relations, the retention of industrial loads, and the need to defer expensive new generating capacity. These general utility objectives can then be translated into more specific load shape objectives that will guide the utility's choice of DSM approaches. A utility might focus on the traditional load management objectives of peak clipping, valley filling, and load shifting. However, some utility planners have other load shape objectives—strategic conservation, strategic load growth, and flexible load shape. The Southern California Edison effort, for example, sought to implement valley filling, whereas New England Electric System is using peak clipping, load shifting, and strategic conservation.

The next major step in an IDSMA case study is a market segmentation analysis to pinpoint those industries that can best help the utility meet its load shape objectives. A variety of factors are used in these segmentation analyses, including employment, output, production capacity, capital investment, exports, and energy consumption. However, these factors are boiled down into just two primary criteria: the growth trends of the industry and the energy consumption of the industry.

Industrial growth is a plus for this type of program because many DSM options require changes in process designs and facility layouts; such changes are much easier to make when growth is taking place and new industrial capacity is being added. Energy consumption is another factor because it is more cost-effective to target those industries that use large amounts of energy per facility.

At the two-digit Standard Industrial Classification (SIC) code level, a growth-energy matrix is the summary result of an IDSMA market segmentation study. The high growth–high energy industries generally offer the greatest DSM potential, and these form the basis for more detailed investigations at the three- and four-digit SIC code levels.

Once the target industries are defined, the next step in a case study analysis is a preliminary investigation of the manufacturing operations and energy use characteristics of the target industries. At this stage, the industries are treated in a generic fashion: flow diagrams are produced to represent the major processes in each industry; energy uses are defined for each major step in the processes; and first-order estimates are made of how electricity use patterns can be modified.

When this information has been collected and considered, the important financial, technical, and contractual elements of a utility-specific industrial DSM program can be outlined. This program must become a product that is marketable to customers within the target industries. Some form of incentive package is needed to entice customers to participate; in most cases, differences in demand and energy charges for peak and off-peak periods provide an incentive for load-shaping activities, such as load shifting.

Often, however, additional incentives are required. For example, up-front incentives are sometimes provided; such incentives help to defray the investment costs a facility faces in implementing any hardware or process changes needed to implement the DSM strategy. A provision of this type of agreement, however, might be an understanding that the DSM load shape changes cannot be reversed for a designated period.

Demonstration test phase

Once an incentive package has been developed, specific customers are identified as likely candidates for involvement in demonstration tests of the IDSMA concept. This

ABSTRACT *Since 1986 EPRI has been cooperating with utilities in an innovative project to apply demand-side management in the industrial sector. Pacific Gas and Electric, Southern California Edison, San Diego Gas & Electric, New England Electric System, and Wisconsin Electric Power have participated in the project's case studies with encouraging results. One participant, Pacific Gas and Electric, set goals of retaining industrial markets and shifting electricity use from peak to off-peak periods. The goals were very successfully accomplished—PG&E shifted approximately 9 MW of demand and added it to off-peak load during the first year.*

process starts with a list of the utility's largest electricity consumers in the target industrial markets. Typically, these customers are contacted to determine their expansion plans and their general interest in participation in a test effort. Each appropriate candidate is then scheduled for a facility "walk through," in which an industrial DSM expert reviews the facility's processes to assess its DSM potential and to suggest useful DSM approaches. On the basis of a review of the walk-through results, several final candidates are selected for participation in the case study's demonstration phase. The industrial DSM expert assists the utility staff in performing detailed engineering and economic analyses that are used to determine the most attractive DSM alternatives.

A variety of DSM alternatives are available for use in the industrial sector. The most significant ones related to the IDSMA project include process rescheduling, capacity addition, thermal and product storage, automation and flexible manufacturing, and electrotechnologies. These strategies can be combined to best suit the needs of each individual facility.

In the Southern California Edison case study, for example, product storage technology plays a prominent role in a proposed demonstration test. This application is ideal for an air separation plant that produces liquid nitrogen and oxygen products. By providing additional nitrogen liquefaction capacity that will operate solely during off-peak hours, over 4 MW of new demand can be brought on-line without adding to peak loads. In addition, over 2 MW of peak load can be shifted to off-peak hours through the use of product storage.

In the New England Electric System case study, a technical analysis found that a demonstration project candidate that processes seafood into frozen fish fillets can employ thermal energy storage, capacity addition, and process rescheduling to reduce approximately 1.4 MW of peak load, a reduction of approximately 40%.

In summary, the IDSMA concept employs a cooperative approach in which a utility and an industrial customer work together. The common goal is to reduce costs for both parties through changes in the way the customer uses electricity. The case study results achieved so far point out the benefits of such an approach.

As more results are obtained, EPRI will present the case studies and the results in a series of workshops. These workshops will provide a forum for discussions about how an increasingly beneficial partnership can be forged between electric utilities and their industrial customers.

Renewable Resource Power Plants

High-Concentration Photovoltaics

by Frank Dostalek, Generation and Storage Division

High-concentration (400× sun concentration or higher) photovoltaics (PV) technology, because of its efficiency and potentially low cell cost, shows promise as an alternative power-generating source in the southwestern regions of the United States. Of the various PV technologies, the high-concentration technology generates the greatest amount of power per square foot of space; a 100-MW high-concentration PV plant would cover less than one square mile of land. Until now, the relatively high cost has impeded the commercialization of this technology. However, this cost is yielding to improved cell efficiencies, innovative engineering, high-yield cell manufacturing, and efficient system designs.

The building blocks of the current EPRI high-concentration PV system are a high-concentration, point-contact silicon cell (1 cm by 1 cm) and cell package (Figure 1); a module (approximately 30 in by 88 in by 12 in) that houses 48 cells and their 500× Fresnel lens systems; and an array (approximately 40 ft^2) placed on a pedestal and driven by a computer-controlled two-axis tracker that continuously points the array at the sun. Each array houses 60 modules that will generate approximately 18 kW.

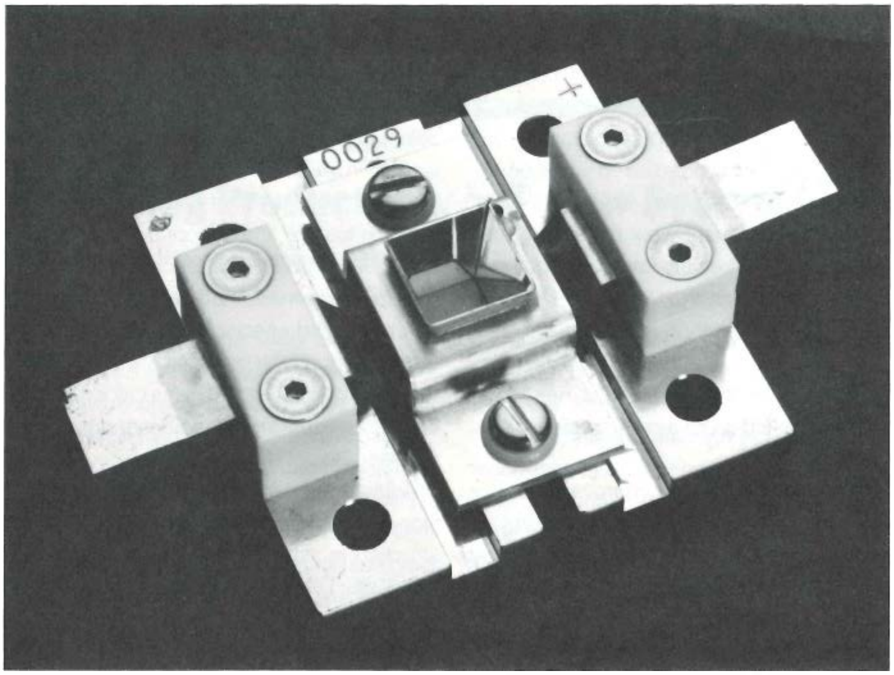
The current program addresses fundamental PV cell research, fundamental silicon material research, cell and cell mount development, Fresnel lens development, module development, and array and system development; it includes a high-concentration PV test program that provides performance evaluation and environmental exposure data.

The EPRI high-concentration PV work has been making steady progress since 1976, when the first EPRI-supported PV cell development work began at Stanford University. By the early 1980s, the Stanford research had resulted in the invention of the Stanford-EPRI point-contact PV (PCPV) cell. This cell has demonstrated conversion efficiencies of 28% at 200 suns sunlight concentration level—a world record for a silicon solar cell. In addition to the cell development program, EPRI funds a sophisticated PV cell and lens test facility that Stanford maintains on the roof of one of the engineering buildings at the university.

In 1986 Georgia Institute of Technology created a new semiconductor materials research facility. In late 1986 EPRI entered into a contract with Georgia Tech to investigate the materials defects in high-resistivity silicon that affect the performance of high-concentration PCPV cells. Advanced techniques were developed to characterize materials defects in silicon, making it possible for raw materials specifications for manufacturing PV cells to be given to silicon crystal and wafer suppliers.

With the invention of the Stanford-EPRI

Figure 1 **A completed cell package. EPRI's high-concentration photovoltaic system contains 48 silicon cell packages to a module. Each cell package is tested before being installed in a module; 60 modules are capable of generating close to 18 kW.**



PCPV cell and steady industry progress in the development of PV technology, EPRI began laying the groundwork for transferring this technology from the university laboratory to commercial production and application.

Module development

In late 1986 high-concentration module development work was initiated at Cummings Engineering. Similar to a baseline design developed by Black & Veatch, the Cummings module is made up of four rows of 12 cells and is 86 in long, 30 in wide, and 12 in deep; it is covered by two 4-lens-by-6-lens Fresnel parquets. Six of these modules have been deployed, and several others are planned.

The first, form-fit, module, completed in early 1987, was a design check to ensure proper fit. After thermal stress and electrical isolation tests were completed, this unit was mounted on the roof at Cummings Engineering in Wilmington, Massachusetts, and used for exposure testing. To date, the unit has over 14,000 total hours of exposure with no major component failures.

The second, thermal, module was completed and deployed in June 1987 at Georgia Power's Shenandoah Solar Center in Newnan, Georgia. This unit was instrumented with 59 thermocouples to evaluate its thermal behavior under actual operating conditions. The unit was moved to Arizona Public Service's STAR (solar test and research) facility at Tempe, Arizona, to continue the thermal tests and now has over 11,000 total exposure hours. No major components have failed.

The third, optical, module was deployed at the Shenandoah Solar Center in September 1987. This module was fitted with dummy cell targets to evaluate the alignment of Fresnel lenses and cells within the module under operating conditions on a tracker. Photographs were taken of the light patterns on the targets. The results of this evaluation led to a revised lens design.

The fourth, electrical, prototype module contained the first 48 cells made in the Acrian, Inc., pilot production line. This module was placed on the tracker at the Shenandoah Solar Center in November 1987, and performance evaluations begun then are still in progress. The next prototype electrical module was deployed in January 1989.

A second-generation module, which is one-tenth the cost and one-half the weight of the first-generation module, has been designed, and a form-fit unit was built to check the new design. A thermal module was deployed and tested by Cummings Engineering in November 1988. As new cells become available, a second-generation prototype electrical module will be deployed and tested.

ABSTRACT *EPRI is sponsoring a broad range of projects aimed at the development and demonstration of high-concentration photovoltaic power systems suitable for large-scale use by electric utilities with excellent sunlight resources. If successful, these systems will incorporate as key features state-of-the-art technology, manufacturability, ease of installation, low operation and maintenance cost, minimal environmental impact, and high performance at costs competitive with standard power-generating options available to the utility industry in the mid- to late 1990s.*

System development

As progress was being made in the development of the Stanford PCPV cell, EPRI began to build a knowledge base for the deployment of systems in the field. In 1983 EPRI contracted with Black & Veatch to do preliminary system conceptual designs and make cost and performance estimates for this type of technology. With the preliminary system design studies completed in 1984, B&V concluded that fixed flat-plate, one- and two-axis flat-plate tracking, and two-axis tracking high-concentration systems were promising power generation options, and that high-concentration PV systems would be particularly attractive for southwestern utilities.

B&V also developed conceptual designs for high-concentration modules and arrays, including the high-concentration (500×) Fresnel lens optics for use with the present PCPV cell design. Single Fresnel lenses and a 4-lens-by-6-lens Fresnel parquet were made for use with the PCPV cell. Lens testing and characterization proved to be a challenge. B&V designed and built a computer-driven lens- and cell-testing unit that is currently being used at the Stanford PV test facility.

Precision Optics built another lens evaluation system that focused the sunlight pattern captured by the test lens on a vidicon sensor. A computer was used to evaluate how well the lens distributed the light pattern at the surface of a PCPV cell.

After review of what was learned from the evaluation of the first lens design, L. W. James and Associates designed a revised lens. The lens tooling was made at Fresnel Optics, and sample lenses have been made. Tests comparing the two lenses were completed in November 1988, and researchers will determine which design gives better performance.

The B&V cell package, lens, module, and array designs were used as a baseline from which further development of the components has been carried out; these are used in the current EPRI array design.

Cell manufacturing development

In 1985 EPRI contracted with Acrian to demonstrate the feasibility of fabricating a point-contact cell outside a research laboratory environment and to set up a pilot production facility. This work has been cofunded by four utility companies—Arizona Public Service, Georgia Power, Pacific Gas and Electric, and Southern California Edison—which have shared the project costs in addition to their general EPRI membership payments. In 1986 Acrian was also contracted to work on improving the cell-mounting package design. The cell development work done by Acrian proved to be extremely important: not only did it show that the PCPV cell can be made by employing standard semiconductor processing techniques, it also identified key areas in which more work was needed in order to make the cell a commercially viable product.

The areas that needed improvement were related to cell design and process refinements. The most important discovery at Acrian, however, was the fact that cell performance deteriorated with exposure to sunlight, particularly the ultraviolet wavelengths. Cell performance degradation amounted to approximately 25–30% of the initial cell performance.

Researchers from Stanford are currently studying the mechanisms responsible for this loss of cell performance. Initial efforts to overcome the problem have been encouraging; however, further testing in sunlight and under accelerated exposure conditions must be carried out to confirm the early findings. The currently favored performance stabilization technique would reduce cell performance by approximately 1% (from 27% to 26%). There would be no significant impact on the manufacturing procedure for the cell or on the cell's cost.

Stanford researchers have continued to work on refining the design of the PCPV cell and have increased cell conversion efficiencies to 28.5%, with a goal of 30%.

EPRI issued an RFP in July 1988 for the next phase of development and commercialization of the PCPV cell. Two companies were selected to continue this work, and contract negotiations are currently in progress at EPRI. Work on the next phase is expected to begin later this year.

Array development

The next basic building block of a utility-scale PV power-generating system is the array. Array development work began in late 1987 with Bechtel Group, Inc., and Scientific Analysis, Inc., as contractors. Preliminary designs were completed by June 1988, and two were selected for evaluation. The two designs are similar: in each the array is supported by a pedestal, is driven by a computer-controlled two-axis tracker, and supports a 5-by-12 matrix of 60 modules. The Bechtel array structure uses a porous module arrangement to decrease wind effects. In the Scientific Analysis design, all the modules are mounted in the same plane. Current plans call for evaluation of both designs at the Shenandoah Solar Center.

A final review of the Scientific Analysis design was completed in November 1988. Construction is scheduled to be completed by mid-1989. The second prototype is to be constructed later in 1989. The performance evaluation of these prototypes will be carried out over a two-year period.

Because of the similarity of the two array designs, a side-by-side test will be done using identical pedestals, two-axis gear drives, and array controls to determine the optimal structure design and module arrangement on the array structure. Site preparation at Shenandoah is in progress, and the pedestals and tracker drives, purchased from ARCO Solar, have been in operation since the end of 1988. To ensure comparable performance of the tracking units, an evaluation of their tracking accuracy will be performed before the array structures are placed on them.

The next major phase of this program, planned for the early 1990s, calls for the deployment and testing of several complete systems in the 100- to 300-kW range, totaling 1 MW. These systems are to be installed at cosponsor utility sites and will give these utilities hands-on operating experience with this new PV power-generating technology. If the development and testing programs proceed as planned, sufficient information on prospects for this technology will be commercially available by the mid-1990s.

When the 1-MWe high-concentration PV

demonstration is completed, the cost for the fabrication and installation of a utility-scale PV power-generating station will be well understood. The current goal for installed cost is approximately $2000 per kW, leading to energy costs of $0.06–0.08 per kWh.

Many reports and documentary videos on the EPRI PV program are available from the Research Reports Center. Also, the *EPRI Journal* has published several articles on the PV program (e.g., July/August 1983, December 1985, January/February 1987).

Computer Simulation and Diagnostics

Enhancing Productivity in Power System Control Centers

by David Curtice, Electrical Systems Division

Managing the huge inflow of changing information in power system control centers is becoming an increasingly complex task. In addition to handling normal operating problems, system operators and dispatchers must be able to deal effectively with power system contingencies caused by severe weather conditions, equipment failures, and other abnormal conditions. Faced with the loss of one or more network components, control center operators must not only restore the power system promptly, but also prevent the development of further contingencies without overloading and damaging key facilities.

Recent trends in U.S. energy use and in the utility industry's operating practices are creating new challenges for power system operators. Commercial interchange of energy—involving both utilities and new generation sources such as wind parks, low-head hydro, and industrial cogeneration—is on the rise. Such developments have increased the complexity of information processing and decision making and added to the stress on operators and dispatchers.

Power system control is semiautomatic, relying on computers to handle many of the monitoring and calculating chores. In the final analysis, however, it is the system operators and dispatchers who are responsible for running the nation's power systems. Although the tremendous expansion in the information-processing capabilities of computers has reduced some of the uncertainties faced by operators, replacing manual switching with keyboard controls has raised the potential for exceeding an individual operator's ability to assimilate critical information. In a crisis, such a situation could extend a period of interruption rather than shorten it.

To help control center operators reduce the occurrence of system outages and preserve system security, EPRI's Electrical Systems Division has undertaken several projects to increase productivity and efficiency and develop better tools and training. These include developing an advanced computer-based power system simulator for operator training, and applying the emerging science of knowledge engineering to support operator decision making in contingency management.

Operator training simulators

Because the safe operation of power systems is greatly dependent on the expertise of control center operators and dispatchers, the importance of training and improving the skills of technical personnel cannot be overemphasized. The increasing demands of an information-oriented society for high-quality electricity service do not tolerate power supply interruptions or voltage drops of even a fraction of a second.

Classroom and on-the-job training cannot fully prepare operators to respond to the full range of system contingencies that can occur during major disturbances. Crises such as the Northeast power blackout of 1965 showed that it is difficult for operators to respond to a situation they have never encountered before. Also, because problems of this magnitude occur infrequently, it is impractical for operators to train on actual operating systems.

ABSTRACT *As the nation's power systems grow ever more complex, control center operators and dispatchers face unprecedented challenges. Trends such as industrial cogeneration and increased power transactions among utilities have escalated demands for information processing and decision making, both for normal operation and for contingency management. Two new computer technologies—an advanced operator training simulator and an expert system for fault analysis and power restoration—promise to reduce stress on control center personnel and enhance power system security.*

A computer-based simulator that can realistically portray an entire power system—complete with generators, transmission lines, and substations—allows trainees to obtain years of experience in a short time without jeopardizing customer service or damaging equipment.

An operator training simulator (OTS) uses mathematical models to simulate the static and dynamic behavior of the power system. Like an airplane flight simulator, the OTS gives power system operators a chance to experience a crisis situation as if it were occurring in real time. Teams of operators who have responsibility for different parts of the system can be trained together, and procedures can be repeated as often as needed. This opportunity for dynamic, realistic training enables operators to master the skills necessary for coping with actual system faults and increases their confidence in their ability to handle crisis situations. Furthermore, improved training enhances the economy and security of the system under normal operating conditions.

There are two types of power system simulators: stand-alone simulators and simulators linked to the standby computers of an on-line energy management system. The stand-alone computer can provide a wide variety of training functions and can train many people at the same time; its major disadvantage is the lack of on-line data. The standby simulator receives on-line data from the trainees' own power system, but the number of training functions is limited by the necessity of sharing equipment used for actual power system monitoring and control, and large numbers of personnel cannot be trained at one time.

In 1984 EPRI initiated work on an advanced OTS (RP1915). The objective was to use EPRI's R&D resources to develop and demonstrate a stand-alone training simulator with extended capabilities. The development guidelines are sufficiently comprehensive to allow integration of the OTS into any existing or planned energy management system. Member utilities will be able to tailor the system to their specific training needs.

In 1985 EPRI chose Philadelphia Electric Co. (PECO) as host utility to develop and demonstrate the OTS. The system includes mathematical models for power simulation, models for the transmission network, and a PECO-specific man-machine interface. The EPRI simulator's major feature is that it is an independent and portable unit adaptable to any energy control system.

The training facility at PECO (Figure 1) consists of a separate room in the control center equipped with two mainframe computers—a Unisys computer for the control center model (CCM) and a CDC Cyber computer for the power system model (PSM). The facility will include two trainee positions and two instructor positions. From an elevated platform behind the trainees, the instructors will monitor the trainees' actions and interact with the CCM and PSM computers.

Trainees will observe system conditions through consoles and a system mimic identical to those used in the control room. The simulator will present them with system scenarios, they will take appropriate actions, and the simulator will respond in a manner that emulates the real system. Instructors will be able to provide feedback both during and after an exercise. They can stop the simulation, confer with the trainees, and then either resume or replay the exercise.

The OTS is scheduled for installation at PECO in 1989. PECO plans to conduct workshops to demonstrate the features of the new simulator. EPRI researchers will conduct a critical analysis of the first two years of operation to conclude the project. Following completion of the project, PECO will take possession of the simulator.

Expert systems

Power system operators and dispatchers must translate great quantities of numerical data into information for assessing power system performance. In addition, there will be periods when they must sort through more than 600 alarms per minute—and, under emergency conditions, as many as 2000 in 15 seconds. Under such circumstances, operators can easily experience data overload that could limit their effectiveness in handling emergencies.

Knowledge engineering, a branch of artificial intelligence, has the potential for converting voluminous data into more usable information. This technology is based on the input of true experts in a field: it is the distillation of their years of learning and judgment.

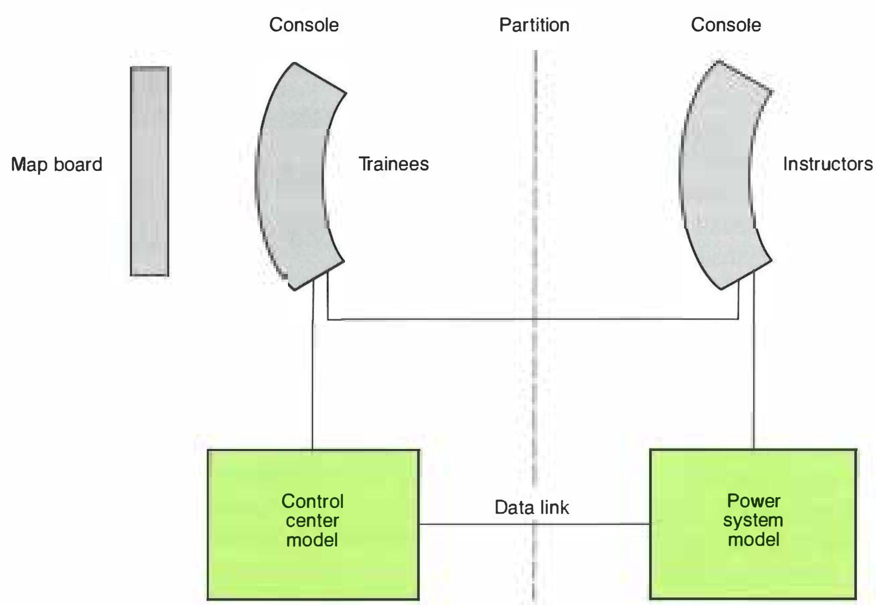


Figure 1 In the operator training simulator configuration, trainees and instructors are separated by a glass partition and work from identical systems that are connected to the control center model and the power system model, respectively. A data link connects the CCM to the PSM, providing an exact replica of the trainees' work environment.

The information is encoded into interactive computer software called an expert system. Such programs can put the problem-solving approaches of these experts at the fingertips of properly trained but less experienced users. Expert systems can give a user information about what is happening on a power system and also suggest remedial actions when something goes wrong. Ultimately, expert systems should be able to diagnose power system problems, provide operators with analyses of system malfunctions, and suggest preventive or corrective actions.

To develop a knowledge-based program, the information extracted from the experts is encoded as rules. An advantage of expert systems over conventional software languages is that changes and additions to the rules can be made without resorting to fundamental programming changes. Expert systems cannot have a deep theoretical understanding of the domains they address. Rather, an expert system is characterized by an explicit rule-based representation of knowledge. An inference mechanism performs the rule-chaining search to form a line of reasoning for solving the problem. Separating knowledge from the general inference method makes it possible to modify or expand a rule-based expert system with less effort than would be necessary in conventional procedural languages.

Under RP1999-7, a comprehensive investigation of the use of expert systems in power system operations, EPRI demonstrated that these programs hold promise for solving power system analysis problems. After investigating 16 potential applications of expert systems, researchers identified one application that met all their feasibility criteria: contingency selection for security assessment. In October 1985, EPRI and Puget Sound Power & Light Co. cosponsored the development and testing of a prototype expert system (RP1999-9). The customer restoration and fault testing (CRAFT) system helps dispatchers perform on-line analyses to locate faults that have caused transmission line outages.

On the recommendation of Puget Power dispatchers, CRAFT is designed to identify and isolate the faulted section in a multitapped line when automatic switching is insufficient to maintain service to all customers on the line. The object is to quickly restore service to customers while maintaining safe operation of the power system. This is an excellent trial problem for an expert system because it requires a speedy operator response based on judgment, experience, and analysis. Because dispatchers are experienced in solving this type of problem, there is an identified source of knowledge for verification. Moreover, an expert system could respond at least as fast as a human operator and would not be distracted by confusing emergency conditions.

To develop CRAFT's knowledge base—approximately 350 rules for fault isolation and service restoration—the project team interviewed several experienced Puget Power dispatchers. They then incorporated the rules in an OPS83 expert system running on a DEC MicroVAX II computer. After simulating problems and comparing the results with dispatcher-proposed actions, they revised and fine-tuned the rules. In a test, the prototype CRAFT system recommended taking the same actions that Puget Power dispatchers would have taken. CRAFT promises to reduce time-consuming manual tasks, minimize outage duration, and serve as a double check for the dispatcher.

As part of the prototype project, investigators studied two approaches for implementing an expert system in the control center: an appended approach, which would install the expert system on a separate computer linked to the control center computer, and an embedded approach, which would integrate the expert system into the control center computer. The advantage of the appended approach would be minimal disruption of the control center computer's operation and displays. The disadvantages would be slower operation of the expert system than if it were integrated into the real-time control center environment, and inability of operators to use familiar standard displays. For a first implementation, however, the appended approach appeared most practical.

Under RP2944-1, Puget Power and the National Science Foundation are cofunding implementation of the CRAFT expert system in the Puget Power control center for evaluation by power system dispatchers. CRAFT has been on-line at Puget Power in an appended configuration since July 1988. A MicroVAX II computer is linked to the supervisory control and data acquisition (SCADA) computer. On the MicroVAX side, the interface programs are written in Fortran. On the SCADA side, both Fortran and assembly languages are used. To date, CRAFT has been tested for 50 of the approximately 65 Puget Power lines that have automatic switches. The general nature of the rules embedded in CRAFT made it possible to expand a small initial set of lines to 50 lines with the addition of only five rules.

Expert systems are still a relatively new area of research. To enhance user-friendliness, the University of Washington is developing tools that can explain why and how a decision is made and that can help the programmer detect inconsistencies in the rules. In the long run, incorporating expert systems in the control center computer will increase efficiency and create a closer interface between programs.

New Contracts

Project	Funding/ Duration	Contractor/EPRI Project Manager
Customer Systems		
Industrial Demand-Side Planning Data (RP2885-1)	$30,000 1 month	Battelle, Columbus Laboratories/*R. Squitieri*
Assessment of Power Quality Concerns at the Customer Level (RP2935-13)	$124,800 8 months	Electrotek Concepts, Inc./ *M. Samotyj*
Energy Lifestyles (RP2979-3)	$40,000 7 months	DOE/*L. Lewis*
Electrical Systems		
Demonstration Systems: Transmission Line Digital Protection and Control (RP1359-18)	$100,000 3 months	Westinghouse Electric Corp./*L. Mankoff*
Centrifugal Processing of Superconductors (RP4000-2)	$62,400 7 months	Battelle Memorial Institute/ *D. Sharma*
Electrical, Thermal, Mechanical, and Chemical Evaluation of PPP and Associated Fluids From a Dissolved-Gas Analysis Standpoint (RP7910-1)	$30,000 2 months	Detroit Edison Co./ *T. Rodenbaugh*
High-Temperature Superconductor Motor Development (RP7911-2)	$875,200 28 months	Reliance Electric Co./ *D. Sharma*
Environment		
Biogeochemical Fate of Mercury in the Aquatic Ecosystem (RP2020-10)	$200,000 2 months	Wisconsin Dept. of Natural Resources/*D. Porcella*
Estimation of Historical Residential Magnetic Fields (RP2964-3)	$27,900 11 months	Southern California Edison Co./*L. Kheifets*
Exploratory Research		
Thermodynamic Cycles for Utilizing Gases in Power Plants (RP8000-39)	$149,600 16 months	Energy Storage & Power Consultants/*A. Cohn*
Application of Photoconductive Switches in AC Circuit Protection (RP8001-8)	$199,400 23 months	University of Florida/ *H. Mehta*
Sulfur Species in Coal (RP8003-19)	$73,000 7 months	Argonne National Laboratory/*H. Lebowitz*
Dry Cleaning of Coal in an Air-Fluidized Bed Phase 2 (RP8006-14)	$50,000 31 months	Lehigh University/ *C. Harrison*
Generation and Storage		
Effect of Quenching Media on Mechanical Properties of CrMoV High-Purity Rotor Manufacturing (RP1403-36)	$49,800 1 month	Japan Steel Works, Ltd./ *R. Jaffee*
Production and Testing of a Large Batch of Synthetic Lightweight Aggregate: Phase 2 (RP1459-26)	$376,700 12 months	Praxis Engineers, Inc./ *N. Hertz*
Computer-Based Training System for Fluidized Combustion (RP2303-30)	$25,500 2 months	HyperMedia Group/ *S. Drenker*
Morony & Cochrane Dam Stability Data (RP2917-17)	$29,900 32 months	Montana Power Co./ *D. Morris*
Application of Fuel Cells to Electric Power Systems (RP2930-1)	$360,000 24 months	Fluor Technology, Inc./ *C. Siebenthal*

Project	Funding/ Duration	Contractor/EPRI Project Manager
Perchloroethylene Extraction Process (RP3027-1)	$102,200 3 months	Midwest Ore Processing Co./*C. Kulik*
Commercial Prototype Upstream Reboiler H_2S System (RP3035-1)	$50,000 2 months	Pacific Gas and Electric Co./*E. Hughes*
Automated NERC GADS Data Analysis System (RP3070-7)	$29,600 3 months	ARINC Research Corp./ *J. Weiss*
Nuclear Power		
Extension of Hot Standby Leakage Detection Period (RP1757-77)	$30,400 6 months	Novetech Corp./*S. Tagart*
Stress Corrosion Cracking of Alloy 718 in High-Temperature Water (RP2181-7)	$30,000 2 months	Rensselaer Polytechnic Institute/*L. Nelson*
Westinghouse Main Stream Safety Valve Technical Subgroup (RP2233-21)	$41,900 6 months	Continuum Dynamics, Inc./ *J. Hosler*
Erosion-Corrosion Single- and Two-Phase Flow Tests (RP2420-72)	$322,600 14 months	Siemens/*B. Chexal*
Improving Polymer Life: Thermal History Fingerprint (RP2614-32)	$120,000 17 months	University of Tennessee/ *G. Sliter*
Self-Collider Fusion Reactor With Direct Energy Conversion (RP2614-42)	$204,400 12 months	University of Florida/ *D. Worledge*
Laboratory and Computational Iodine Studies for the Advanced Containment Experiments, Phase B (RP2802-16)	$275,000 12 months	Martin Marietta Energy Systems, Inc./*R. Ritzman*
Evaluation of Acoustic Emissions for Detection of Crack Initiation in Stainless Steel (RP2812-7)	$76,000 6 months	Battelle, Pacific Northwest Laboratories/*R. Pathania*
Alarm Processing and Diagnostic System Using NASA Technology (RP2902-4)	$816,300 24 months	Bechtel Group, Inc./ *J. Naser*
Pilot Data Base Management System Development: Equipment Performance in Earthquakes (RP2925-6)	$183,800 9 months	EQE, Inc./*R. Kassawara*
Performance Monitoring of Cables With Local Degradation (RP2927-5)	$533,000 20 months	Sandia National Laboratories/*G. Sliter*
Backscatter Gamma-Ray Imaging for Detecting Pipe Wall Thinning (RP2974-1)	$30,000 10 months	Pennsylvania State University/*S. Liu*
Resin Separability Demonstration to Improve Polishing Under Morpholine All-Volatile Treatment (RP2977-1)	$99,600 11 months	RCT, Inc./*D. Passell*
Oxygen Transport in BWR Steam Cycles (RP2977-3)	$35,000 3 months	San Diego State University Foundation/*D. Passell*
Planning Systems for Core Shuffles (RP3003-1)	$394,000 18 months	Combustion Engineering Inc./*J. Naser*
Evaluation of Fault-Tolerant Digital Control System Architecture (RP3008-1)	$99,100 8 months	Martin Marietta Energy Systems, Inc./*B. Sun*
Physics Benchmarking to Resolve Modern LWR Uncertainties (RP3013-1)	$124,400 14 months	S. Levy, Inc./*W. Eich*
Planning and Evaluation		
Dynamic Pricing of Decentralized Power Systems (RP2996-5)	$30,400 12 months	Laurits R. Christensen Associates, Inc./*H. Mueller*

New Technical Reports

Requests for copies of 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, U.S. universities, or government agencies. 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 EPRI reports on request. For information on how to order one-page summaries of reports, call the EPRI Hotline, (415) 855-2411.

CUSTOMER SYSTEMS

Power Utilization in Flat Processing of Steel
EM-5996 Final Report (RP2570-1); $32.50
Contractor: EPRI Center for Metals Production
EPRI Project Manager: R. Jeffress

Ground-Source and Hydronic Heat Pump Market Study
EM-6062 Final Report (RP2792-5); $47.50
Contractor: Technical Marketing Associates, Inc.
EPRI Project Manager: P Joyner

A Guide to Annual Marketing Planning
EM-6087 Final Report (RP2671-1); $32.50
Contractor: QEI, Inc.
EPRI Project Manager: L. Lewis

Cogeneration and Utilities: Status and Prospects
EM-6096 Final Report (RP1276-23); $32.50
Contractor: Synergic Resources Corp.
EPRI Project Managers: C. Gellings, H. Gransell

COGENMASTER—A Model for Evaluating Cogeneration Options, Vols. 1 and 2
EM-6102 Final Report (RP1276-23); Vol. 1, $1000; Vol. 2, $1000
Contractor: Synergic Resources Corp.
EPRI Project Manager: H. Gransell

Proceedings: Meeting Customer Needs With Heat Pumps—1987
EM-6107 Proceedings (RP2597-9); $47.50
Contractor: Policy Research Associates, Inc.
EPRI Project Manager: M. Blatt

Proceedings: End-Use Power Quality R&D Planning
EM-6109 Proceedings (RP2935-1); $25
Contractor: TEM Associates, Inc.
EPRI Project Manager: M. Samotyj

Evaluation of Passive Monitors for Measuring Indoor Radon and Formaldehyde
EM-6122 Final Report (RP2034-1); $32.50
Contractor: GEOMET Technologies, Inc.
EPRI Project Manager: J. Kesselring

Status of Least-Cost Planning in the United States
EM-6133 Final Report (RP2982-2); $100
Contractor: Barakat, Howard & Chamberlin, Inc.
EPRI Project Manager: W. Smith

The Food-Service Industry: A Presentation Package With Supporting Text
EM-6148 Final Report (RP2890-1); $32.50
Contractor: Hart, McMurphy & Parks, Inc.
EPRI Project Manager: K. Johnson

Measurement of Differential Pressures and Radon Entry in Research Houses and Evaluation of Radon Control Methods
EM-6151 Final Report (RP2034-1); $32.50
Contractor: GEOMET Technologies, Inc.
EPRI Project Manager: J. Kesselring

ELECTRICAL SYSTEMS

Second Workshop of the Italy/USA Cooperation in Electric Power Transmission
EL 6018-SR Proceedings; $32.50
EPRI Project Manager: R. Kennon

Study of Improved Load-Tap-Changing for Transformers and Phase-Angle Regulators
EL 6079 Final Report (RP2763-1); $32.50
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: S. Lindgren

Static Electrification Control in Power Transformers
EL 6081 Final Report (RP1499-7); $32.50
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: S. Lindgren

DCGRND and ACDCFLT Computer Models and User's Manuals
EL-6106 Interim Report (RP1494-6); $32.50
Contractor: Georgia Institute of Technology
EPRI Project Manager: G. Addis

Concurrent Computation of Power System Reliability
EL 6125 Final Report (RP2473-16); $25
Contractor: Northwestern University
EPRI Project Manager: M. Lauby

Induction Motor Modeling in Stability Simulation
EL 6126 Final Report (RP2473-2); $25
Contractor: Minnesota Power
EPRI Project Manager: M. Lauby

Static Electrification in Refrigerant 113
EL-6138 Final Report (RP1536-8, -9); $32.50
Contractor: General Electric Co.
EPRI Project Manager: V. Tahiliani

Computer-Aided Relay Protection Coordination
EL 6145 Final Report (RP2444-2); $40
Contractor: University of Washington
EPRI Project Manager: D. Maratukulam

ENVIRONMENT

Air Emissions Risk Assessment Model (AERAM) Manager: User's Guide, Version 1.0
EA-5886-CCM Computer Code Manual (RP1826-18); $25
Contractor: IWG Corp.
EPRI Project Manager: A. Thrall

Leachate Chemistry at the Montour Fly Ash Test Cell
EA-5922 Interim Report (RP2485-8); $32.50
Contractor: Battelle, Pacific Northwest Laboratories
EPRI Project Manager: I. Murarka

Interim Emissions Inventory for Regional Air Quality Studies
EA-6070 Interim Report (RP1630-23); $40
Contractor: ENSR Consulting and Engineering
EPRI Project Managers: R. Patterson, P. Mueller

Proceedings: Innovative Approaches in Cancer Risk Assessment
EA-6072 Proceedings (RP1826-17); $40
Contractor: Clement Associates, Inc.
EPRI Project Manager: A. Silvers

A Hierarchy of Dynamic Plume Models Incorporating Uncertainty, Vol. 1: Overview
EA-6095 Final Report (RP1616-28); $40
Contractor: ARAP Division, California Research & Technology, Inc.
EPRI Project Managers: G. Hilst, G. Beals

Radiation Worker Health Study: Scoping Phase
EA-6112 Final Report (RP2920-1); $32.50
Contractor: Epidemiology Resources, Inc.
EPRI Project Manager: L. Kheifets

Exposure to Acidic Sulfates in the Atmosphere: Review and Assessment
EA-6150 Final Report (RP940-5); $32.50
Contractor: Frederick W. Lipfert
EPRI Project Manager: R. Wyzga

EXPLORATORY RESEARCH

Sintering and Creep of Copper, Nickel, and Alloys
ER-6065 Final Report (RP2278-4); $25
Contractor: Northwestern University
EPRI Project Manager: W. Bakker

Proceedings: 1987 Workshop on Coal Structure
ER-6099-SR Proceedings; $40
EPRI Project Manager: L. Atherton

GENERATION AND STORAGE

FGD Chemistry and Analytical Methods Handbook, Vol. 2: Chemical and Physical Test Methods, Revision 1
CS-3612 Final Report (RP1031-4); $500
Contractor: Radian Corp.
EPRI Project Manager: R. Moser

AFBC Conversion at Northern States Power Company, Vol. 3: Demolition and Relocation
CS-5501 Final Report (RP2628-3); $100
Contractor: Stone and Webster Engineering Corp.
EPRI Project Manager: S. Tavoulareas

Remaining Life Estimation of Boiler Pressure Parts, Vol. 1: Identification of Relevant Damage Mechanisms
CS-5588 Final Report (RP2253-1); $400
Contractor: Combustion Engineering, Inc.
EPRI Project Managers: R. Viswanathan, R. Townsend

Conceptual Design of a 100-MW Fuel Cell Power Plant for Urban Utility Applications
AP-5609 Final Report (RP1777-1); $32.50
Contractor: International Fuel Cells
EPRI Project Managers: D. Rastler, C. Siebenthal

Soft-Start Fuel Control Modifications for Large, Heavy-Duty Combustion Turbines
AP-5975 Final Report (RP2102-17); $32.50
Contractor: Battelle, Columbus Division
EPRI Project Managers: L. Angello, G. Quentin

Pilot-Scale Combustion Characterization of Two Illinois Coals
CS-6009 Final Report (RP2425-1); $40
Contractor: Combustion Engineering, Inc.
EPRI Project Manager: A. Mehta

Workshop Proceedings on Defining Coal Handleability: Its Cost Impact and Control
CS-6015 Proceedings (RP1400-6, -11); $200
Contractor: Kaiser Engineers, Inc.
EPRI Project Managers: J. Hervol, C. Harrison

Using Optical Pyrometry to Measure Gas Turbine Blade Metal Temperatures
AP-6020 Final Report (RP2102-3); $40
Contractor: Solar Turbines, Inc.
EPRI Project Manager: G. Quentin

Dynamic Simulation and Performance Evaluation of Fossil Power Plants
CS-6047 Final Report (RP1184-11); $32.50
Contractor: Science Applications International Corp.
EPRI Project Manager: M. Divakaruni

Proceedings: 1987 Conference on Fossil Plant Cycling
CS-6048 Proceedings (RP1184-27); $450
Contractor: TRAX Corp.
EPRI Project Managers: M. Divakaruni, G. Poe

Proceedings: 1987 Conference on Control Systems for Fossil Fuel Power Plants
CS-6049 Proceedings (RP2710-1); $425
Contractor: Encor-America, Inc.
EPRI Project Manager: M. Divakaruni

Fossil Plant Startup Advisor, Vols. 1 and 2
CS-6051 Final Report (RP1184-4); Vol. 1, $32.50; Vol. 2, $25
Contractor: Babcock and Wilcox Co.
EPRI Project Managers: M. Divakaruni, G. Poe

Atmospheric Fluidized-Bed Combustion Waste Management Design Guidelines
CS-6053 Final Report (RP2708-1); $800
Contractors: Baker/TSA, Inc.; ICF Technology, Inc.
EPRI Project Manager: D. Golden

Control of Fan Erosion in Coal-Fired Power Plants: Phase 2
CS-6068 Final Report (RP1649-4); $55
Contractors: Westinghouse Research and Development Center; Westinghouse Sturtevant Division
EPRI Project Manager: J. Stringer

Effects of Targeted Chlorination on AL-6X Condenser Tube Corrosion in Seawater
CS-6077 Final Report (RP2300-2); $25
Contractor: Stone & Webster Engineering Corp.
EPRI Project Managers: B. Syrett, W. Chow

Proceedings: 1987 Conference on Expert-System Applications in Power Plants
CS-6080 Proceedings (RP2923-1); $400
Contractor: Expert-EASE Systems, Inc.
EPRI Project Manager: M. Divakaruni

Compact Analyzer for Fossil Plant Simulators
CS-6092 Final Report (RP1184-12); $25
Contractor: Systems Control, Inc.
EPRI Project Manager: M. Divakaruni

Laboratory Testing of Fly Ash Slurry
CS-6100 Final Report (RP2422-2); $55
Contractor: GAI Consultants, Inc.
EPRI Project Manager: D. Golden

AFBVAL User's Guide: Integrated Financial and Engineering Evaluation of AFBC Power Plants
CS-6117-CCM Computer Code Manual (RP2303-12, RP2543-2); $40
Contractor: Decision Focus, Inc.
EPRI Project Manager: S. Tavoulareas

Combustion Turbine Vibration Monitoring: Practices, Trends, Techniques, Selection, and Benefits
AP-6119 Final Report (RP2102-22); $32.50
Contractor: Southwest Research Institute
EPRI Project Manager: G. Quentin

Availability Assessment of 11-MW Phosphoric Acid Fuel Cell Power Plants
AP-6124 Final Report (RP1461-1); $25
Contractor: ARINC Research Corp.
EPRI Project Managers: D. Rastler, J. Weiss

Trace Arsenic Species and Equilibria in Geothermal Fluids
GS-6142 Topical Report (RP2791-1); $32.50
Contractor: San Diego State University
EPRI Project Manager: V. Roberts

Evaluation of a Texaco Gasification–Combined-Cycle Plant With Kraftwerk Union Gas Turbines
GS-6160 Final Report (RP2699-10); $40
Contractor: Fluor Daniel, Inc.
EPRI Project Manager: M. Gluckman

Devon Station Repowering Study, Phase 2: Coal Gasification Facility Conceptual Design
GS-6161 Final Report (RP2699-2); $32.50
Contractor: Northeast Utilities Service Co.
EPRI Project Managers: M. Gluckman, A. Lewis

NUCLEAR POWER

RETRAN-02—A Program for Transient Thermal-Hydraulic Analysis of Complex Fluid Flow Systems, Vol. 1: Theory and Numerics (Rev. 4)
NP-1850-CCM-A Computer Code Manual (RP889-3); $100
Contractor: EI International, Inc.
EPRI Project Manager: L. Agee

PLEX Project Briefs, Revision 1
NP-5388SP Final Report (RP2643-15); $3500
EPRI Project Manager: M. Lapides

Guidelines for the Content of Records to Support Nuclear Power Plant Operation, Maintenance, and Modification (NCIG-08), Vols. 1 and 2
NP-5653 Final Report (RPQ101-4); Vol. 1, $25; Vol. 2, $40
Contractor: Reedy Associates, Inc.
EPRI Project Manager: W. Bilanin

Supplementary Examination of Alternative Materials in a Model Steam Generator, Vol. 1: Tubesheet and Tube Bundle Examinations
NP-5928M Final Report (RPS302-7); $25
Contractor: Combustion Engineering, Inc.
EPRI Project Manager: C. Shoemaker

Supplementary Examination of Alternative Materials in a Model Steam Generator, Vol. 3: Tube Characterization by Metallography and Transmission Electron Microscopy
NP-5928 Final Report (RPS302-7); $32.50
Contractor: Combustion Engineering, Inc.
EPRI Project Manager: C. Shoemaker

VRTECH/PC-II User's Manual: Volume-Reduction Technology Computer Program
NP-5992-CCM Computer Code Manual (RP1557-23); $32.50
Contractor: Analytic Sciences Corp.
EPRI Project Manager: P. Robinson

Human Factors Affecting the Performance of Inspection Personnel in Nuclear Power Plants
NP-6000 Final Report (RP1570-19); $32.50
Contractor: Shay S. Karimi
EPRI Project Manager: M. Behravesh

Waste Acceptance Criteria Study, Vols. 1 and 2
NP-6001 Final Report (RP2717-1); Vol. 1, $32.50; Vol. 2, $40
Contractor: E. R. Johnson Associates, Inc.
EPRI Project Manager: R. Lambert

Implementation Considerations for Digital Control Systems in Power Plants
NP-6004 Final Report (RP2126-8); $25
Contractor: Integrated Systems, Inc.
EPRI Project Manager: B. Sun

Chemical Decontamination Experience at Commonwealth Edison Nuclear Power Plants
NP-6023 Final Report (RP1329-3); $25
Contractor: Niagara Technical Consultants
EPRI Project Manager: C. Wood

Operation of the EPRI Nondestructive Evaluation Center: 1987 Annual Report
NP-6026 Interim Report (RP1570-2); $40
Contractor: J. A. Jones Applied Research Co.
EPRI Project Manager: G. Dau

Stress Corrosion Monitoring and Component Life Prediction: Feasibility Study
NP-6028M Final Report (RP2006-12, -14); $25
Contractor: General Electric Co.
EPRI Project Manager: J. Gilman

Oil Decontamination Survey
NP-6031 Final Report (RP2414-22); $25
Contractor: Science Applications International Corp.
EPRI Project Manager: P. Robinson

Stepped Frequency Imaging for Flaw Monitoring
NP-6033 Final Report (RP2687-4); $25
Contractor: Failure Analysis Associates
EPRI Project Manager: M. Avioli

Assessment of NRC Regulatory Guide 1.150, Revision 1: Implementation and Interpretation
NP-6034 Final Report (RP2943-1); $25
Contractor: Southwest Research Institute
EPRI Project Manager: M. Behravesh

Piping System Damping Evaluation
NP-6035 Final Report (RP2635-2); $47.50
Contractor: Bechtel Group, Inc.
EPRI Project Manager: H. Tang

A Methodology for Assessment of Nuclear Power Plant Seismic Margin
NP-6041 Final Report (RP2722-1); $62.50
Contractors: NTS Engineering; RPK Structural Mechanics Consulting; Pickard, Lowe and Garrick; Woodward-Clyde Consultants; Duke Power Co.
EPRI Project Manager: R. Kassawara

Evaluation of Flaws in Ferritic Piping
NP-6045 Final Report (RP1757-65); $32.50
Contractor: Novetech Corp.
EPRI Project Manager: D. Norris

BWR Top-Guide Integrity: Further Evaluation
NP-6050 Final Report (RP2680-7); $25
Contractor: Structural Integrity Associates, Inc.
EPRI Project Manager: T. Griesbach

Human Performance in Nondestructive Inspections and Functional Tests
NP-6052 Final Report (RP2705-9); $32.50
Contractor: Anacapa Sciences, Inc.
EPRI Project Manager: H. Parris

Utility Response to NRC Bulletin 87-01, Thinning of Pipe Walls in Nuclear Power Plants
NP-6066 Final Report (RP2057-7); $55
Contractor: Science Applications International Corp.
EPRI Project Manager: M. Behravesh

Surveillance of Instrumentation Channels at Nuclear Power Plants, Vol. 1: Methods for Reducing Costs
NP-6067 Final Report (RP2906-2); $25
Contractor: Joseph A. Thie
EPRI Project Manager: R. Colley

Engineering Model of Earthquake Ground Motion for Eastern North America
NP-6074 Final Report (RP2556-16); $40
Contractor: Risk Engineering, Inc.
EPRI Project Managers: C. Stepp, J. Schneider

EPRI Seminar on Data Acquisition, Control, and Communications in Power Plants
NP-6078-SR Proceedings; $62.50
EPRI Project Manager: R. Colley

Intraspect/98 Characterization of a Heavy Section
NP-6082 Topical Report (RP2165-8); $32.50
Contractor: AMDATA, Inc.
EPRI Project Manager: M. Avioli

Oxygen Control in PWR Secondary Coolant
NP-6083 Final Report (RP1571-5); $25
Contractor: Burns and Roe, Inc.
EPRI Project Manager: T. Passell

Cost of Converting to an All-Ferrous PWR Secondary Feedwater System
NP-6084 Topical Report (RP1571-5); $25
Contractors: NWT Corp.; Gibbs & Hill, Inc.
EPRI Project Manager: T. Passell

The Feasibility of Using Electromagnetic Acoustic Transducers to Detect Corrosion in Mark I Containment Vessels
NP-6090 Interim Report (RP1570-21); $25
Contractor: Innovative Sciences, Inc.
EPRI Project Manager: M. Avioli

The LWR Aerosol Containment Experiments (LACE) Project: Summary Report
NP-6094-D Final Report (RP2135); $25
Contractor: Westinghouse Hanford Co.
EPRI Project Manager: F Rahn

Solids Filtration of High-Temperature Feedwater in a PWR Secondary Circuit
NP-6097 Final Report (RP1571-5); $25
Contractors: NWT Corp.; Gibbs & Hill, Inc.
EPRI Project Manager: T. Passell

The Stability Analysis Using Two Fluids (SAT™) Code for Boiling Flow Systems, Vols. 1–4
NP-6103-CCM Computer Code Manual (RP495-2); Vol. 1, $25; Vol. 2, $25; Vol. 3, $25; Vol. 4, $25
Contractor: Arizona State University
EPRI Project Manager: S. Kalra

Parametric Radionuclide Release Calculations Using the MAAP-3.0 Computer Code
NP-6111 Final Report (RP2637-1); $32.50
Contractor: Science Applications International Corp.
EPRI Project Managers: E. Fuller, R. Ritzman

Proceedings: Main Coolant Pump Diagnostics
NP-6116 Proceedings (RP1556-4); $70
Contractor: Ontario Hydro
EPRI Project Manager: J. Weiss

Implementation of a Digital Feedwater Control System at Dresden Nuclear Power Plant Units 2 and 3
NP-6143 Final Report (RP2686-3); $32.50
Contractor: Atomic Energy of Canada, Ltd.
EPRI Project Manager: B. Sun

Design and Operation of a Digital Low-Power Feedwater Control System for PWRs
NP-6149 Final Report (RP2686-4); $32.50
Contractor: Combustion Engineering, Inc.
EPRI Project Manager: B. Sun

An Assessment of Boraflex Performance in Spent-Nuclear-Fuel Storage Racks
NP-6159 Final Report (RP2813-4); $32.50
Contractor: Northeast Technology Corp.
EPRI Project Manager: R. Lambert

On-Site Storage of Low-Level Radioactive Waste at Power Reactors: An International Scoping Study
NP-6163 Final Report (RP2724-3); $32.50
Contractor: Science Applications International Corp.
EPRI Project Manager: P. Robinson

Zinc Injection to Control Radiation Buildup at BWRs: Plant Demonstrations
NP-6168 Interim Report (RP2758-1); $25
Contractor: GE Nuclear Energy
EPRI Project Manager: C. Wood

A Performance-Based Selective Inspection Process (NCIG-09)
NP-6200 Final Report (RPQ101-12); $1000
Contractor: Sargent & Lundy Engineers
EPRI Project Manager: W. Bilanin

PLANNING AND EVALUATION

Office Productivity Tools for the Information Economy: Possible Effects on Electricity Consumption
P/EM-6008 Final Report (RP2345-30); $25
Contractor: Boston Pacific Co.
EPRI Project Managers: O. Yu, O. Zimmerman

Utility Competitive Assessment Methods, Vols. 1 and 2
P/EM-6019 Final Report (RP2937-1); Vol. 1, $250; Vol. 2, $250
Contractor: Putnam, Hayes & Bartlett, Inc.
EPRI Project Managers: S. Feher W. Smith

Proceedings: 1988 Utility Strategic Issues Forum—Planning in a Competitive Environment
P-6181 Proceedings (RP2997); $100
Compiler and Editor: Susan M. Lubonovich
EPRI Project Manager: S. Feher

New Computer Software

The Electric Power Software Center (EPSC) provides a single distribution center for computer programs developed by EPRI. The programs are distributed under license to users. No royalties are charged to nonutility public service organizations in the United States, including government agencies, universities, and other tax-exempt organizations. Industrial organizations, including nonmember electric utilities, are required to pay royalties. EPRI member utilities, in paying their membership fees, prepay all royalties. Basic support in installing the codes is available at no charge from EPSC; however, a consulting fee may be charged for extensive support.

For more information about EPSC and licensing arrangements, EPRI member utilities, government agencies, universities, and other tax-exempt organizations should contact Electric Power Software Center, Power Computing Co., 1930 Hi Line Drive, Dallas, Texas 75207; (214) 655-8883. Industrial organizations, including nonmember utilities, should contact EPRI's Manager of Licensing, P.O. Box 10412, Palo Alto, California 94303; (415) 855-2866.

ADEPT: Acid Deposition Decision Tree Model
Version 2.2 (IBM); EA-2540
Contractor: Decision Focus, Inc.
EPRI Project Manager: Thomas Wilson

AFBVAL: Integrated Engineering and Financial Assessment of AFBC Power Plants
Version 1.0 (IBM-PC); CS-6117
Contractor: Decision Focus, Inc.
EPRI Project Manager: Stratos Tavoulareas

AIRTOX: Air Toxics Risk Management Model
Version 3.0 (IBM-PC)
Contractor: Decision Focus, Inc.
EPRI Project Manager: Thomas Wilson

COGENMASTER: Evaluation of Cogeneration Projects
Version 1.1 (IBM-PC); EM-6102
Contractor: Synergic Resources Corp.
EPRI Project Manager: Hans Gransell

COMMEND: Commercial Section End-Use Energy Demand Forecasting Model
Version 2.1 (IBM); EM-4486
Contractor: Regional Economic Research
EPRI Project Manager: Steven Braithwait

CQIS: Coal Quality Information System
Version 1.0 (IBM-PC); CS-5774
Contractors: Kaiser Engineers, Inc.; Science Applications International Corp.
EPRI Project Managers: Clark Harrison, James Hervol

EFFICIENCY-MAP: Efficiency Maintenance Analysis
Version 1.0 (IBM-PC)
Contractor: Fern Engineering
EPRI Project Manager: Clark Dohner

ESPRE: EPRI Simplified Program for Residential Energy
Version 1.8 (IBM-PC); EM-4523
Contractor: Arthur D. Little, Inc.
EPRI Project Manager: John Kesselring

EXPOCALC: Exposure Assessment Tool for Transmission Line Electric Fields
Version 2.2 (IBM-PC); EA-5765
Contractor: Enertech Consultants, Inc.
EPRI Project Manager: Stan Sussman

GADSRAM: Conversion of NERC GADS Data Files Into UNIRAM Availability Models
Version 1.0 (IBM-PC); AP-6016-CCM
Contractor: ARINC Research Corp.
EPRI Project Manager: Jerry Weiss

NODE-P2: Three-Dimensional PWR Core Simulator
Version 2MOD04 (CDC, IBM); NP-4574-CCM
Contractor: S. Levy, Inc.
EPRI Project Manager: Robert Breen

PIES: Residential and Commercial Reference Load Shapes and DSM Impacts
Version 1.0 (IBM-PC); EM-5767
Contractor: Laurits R. Christensen Associates, Inc.
EPRI Project Manager: Steven Braithwait

SGA-SGSYS: Substation Grounding Analysis
Version 4.0 (IBM)
Contractor: Georgia Institute of Technology
EPRI Project Manager: Gilbert Addis

SMART: Small Artificial Reasoning Toolkit
Version 1.4 (IBM-PC); NP-5645M
Contractor: C. Horne, Inc.
EPRI Project Manager: David Cain

SSSP: Small Signal Stability Program
Version 1.1 (IBM, PRIME, VAX); EL 5798, EL-5798-CCML
Contractor: S. Levy, Inc.
EPRI Project Manager: Mark Lauby

UNSAT1D: Unsaturated Groundwater Flow Model
Version 2.0 (IBM-PC); CS-5512
Contractor: ICF Technology, Inc.
EPRI Project Manager: Dean Golden

CALENDAR

For additional information on the meetings listed below, please contact the person indicated.

APRIL

11–12
Utility Strategic Issues Forum
Kansas City, Missouri
Contact: Sherman Feher, (415) 855-2838

18–20
Workshop: Coal Weighing and Sampling
St. Louis, Missouri
Contact: Clark Harrison, (412) 479-3503

19–21
Management of Manufactured-Gas Plant Sites
Pittsburgh, Pennsylvania
Contact: Ishwar Murarka, (415) 855-2150

25–28
Seminar: Transmission Line Foundations
Palo Alto, California
Contact: Vito Longo, (415) 855-2287

MAY

1–5
Electrical Potpourri Seminar
Palo Alto, California
Contact: James Hall, (415) 855-2305

2–4
Conference: Demand-Side Management
Cincinnati, Ohio
Contact: Steven Braithwait, (415) 855-2606

2–4
Groundwater Quality and Waste Disposal
Washington, D.C.
Contact: Ishwar Murarka, (415) 855-2150

JUNE

5–8
Expert Systems Applications for the Electric Power Industry
Orlando, Florida
Contact: Joseph Naser, (415) 855-2107

5–9
High-Voltage Transmission Line Electrical Design
Palo Alto, California
Contact: James Hall, (415) 855-2305

28–30
1989 Cogeneration Seminar
Boston, Massachusetts
Contact: Hans Gransell, (415) 855-2855

Authors and Articles


DeMeo


Peterson


Barker


Williams

Thin Films: Expanding the Solar Marketplace (page 4) was written by Taylor Moore, senior feature writer for the *Journal,* with technical assistance from two research managers of EPRI's Generation and Storage Division.

Edgar DeMeo, manager of the Solar Power Program for the past nine years, guides research in photovoltaics, solar-thermal, and wind energy technologies. He came to the Institute as a project manager in 1976 after six years on the engineering research faculty at Brown University and two years as an instructor at Annapolis. DeMeo graduated in electrical engineering from Rensselaer Polytechnic Institute and earned MS and PhD degrees at Brown.

Terry Peterson, a project manager in DeMeo's program, specializes in thin-film photovoltaic materials. Before joining EPRI in 1986, he was with Chevron Research Company for eight years, where he became the leader of a solar device fabrication group. Still earlier, he worked in materials and molecular research at Lawrence Berkeley Laboratory. Peterson has a BS degree in physics from the University of California at San Diego, an MS in physics from the University of California at Berkeley, and a PhD in materials science and engineering, also from UC-Berkeley. ■

Innovation and Industrial Development (page 16) reports on problems and solutions voiced by participants at EPRI's 1988 Advisory Council seminar. The article was written by **Brent Barker,** editor in chief of the *Journal* since 1977.

Barker was a writer and communications consultant before he came to EPRI. He earlier worked as an industrial economist at SRI International and a research analyst at USX Corporation. Barker graduated in engineering science from Johns Hopkins University and earned an MBA at the University of Pittsburgh. ■

Fluidized Bed Fires Up at TVA (page 26) was written by Taylor Moore, senior *Journal* feature writer. Moore attended the November 1988 dedication of a big new fluidized-bed combustion demonstration project at the Tennessee Valley Authority's Shawnee power plant in Paducah, Kentucky. ■

Sludgebuster for Steam Generators (page 30) was written by David Boutacoff, *Journal* feature writer, in cooperation with **C. Lamar Williams** of EPRI's Nuclear Power Division.

Williams, a project manager in the Steam Generator Project Office, is involved in the development of operation and maintenance procedures for PWRs. He has been with EPRI since 1979, following six years at Bettis Atomic Power Laboratory, where he investigated patterns of critical heat flux and two-phase flow in steam supply systems. Williams holds BS, MS, and PhD degrees in mechanical engineering from the Georgia Institute of Technology. ■

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

EPRI JOURNAL

March 1989