Photovoltaics for Utilities

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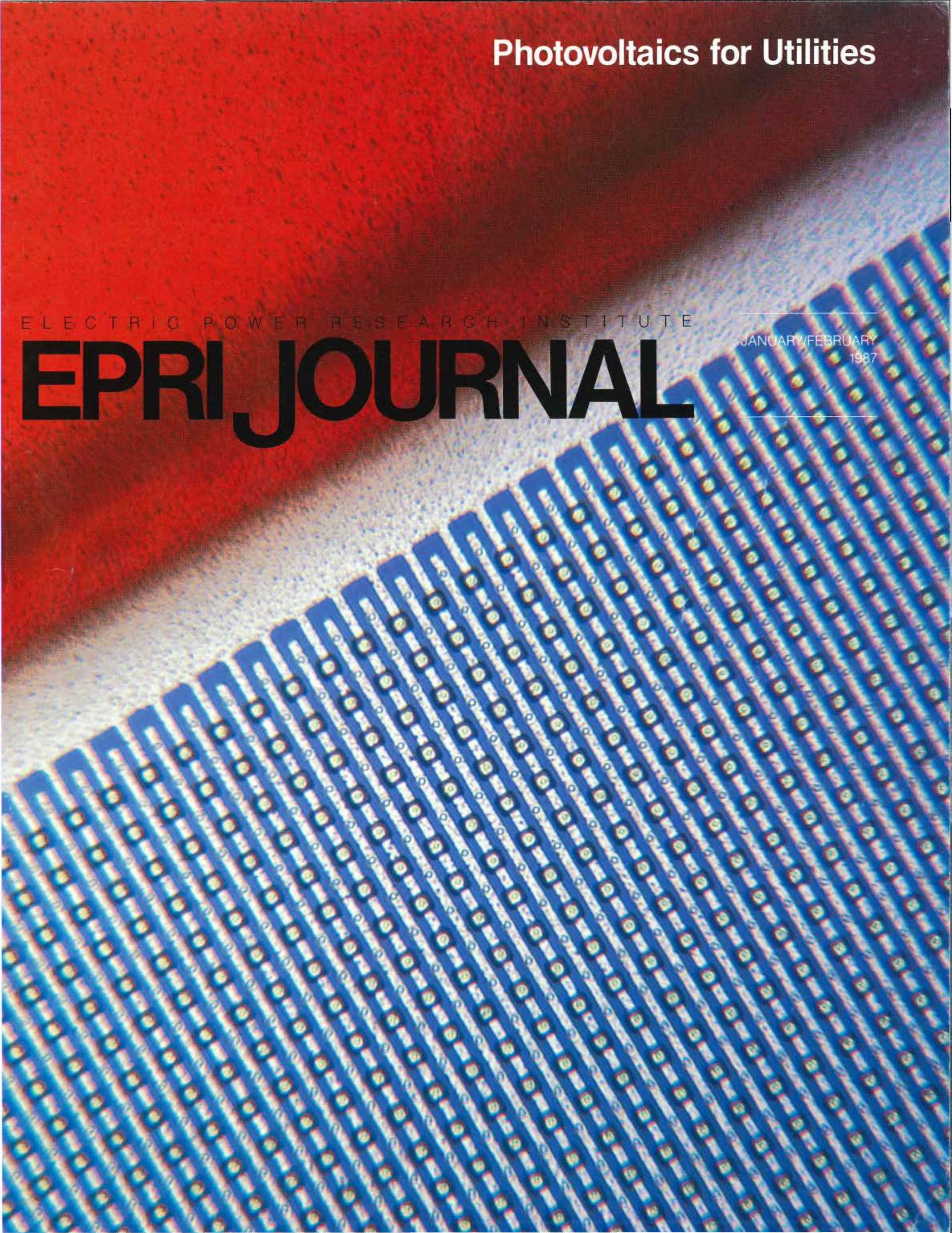

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Cover: A 500-power magnification of the point-contact photovoltaic cell shows off its innovative contact structure, made possible by semiconductor manufacturing techniques. This concentrating cell, with the highest conversion efficiency ever recorded, is the first device with real potential for economic utility bulk power generation.

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Solar Cell Development: You Can't Trust to Luck


Cummings

In the development of the point-contact photovoltaic cell we have witnessed a remarkable achievement. For the first time we have a solar technology in hand that shows real promise for practical utility-scale power generation. As with most productive research, this cell has come primarily as a result of good basic ideas, an innovative technical approach, and a lot of experimental elbow grease. These factors cannot be overrated—you do not achieve the highest cell efficiencies ever documented by luck alone. But the development of the PCPV cell has also demonstrated a subtler truth—you cannot trust to luck in your management approach if you are going to see practical results over the long haul.

In taking control of this project's R&D destiny it was essential to exploit EPRI's ability, by virtue of its structure and stable utility industry support, to provide long-term continuity in funding research. Indeed, EPRI's sponsorship of the PCPV project at Stanford University since March of 1976 provided the environment essential for progress in the exploratory stages. A second key to success was the imposition of specific targets and yardsticks for measuring R&D progress. We started with requirements that fit the goals we knew we would eventually have to meet: not "something better than what we have now" but specifically a cost-effective device designed for use on utility systems. In the device research itself, a detailed model provided the basis for cell design, evaluation, and modification as advancements emerged.

Finally, peer review of progress and the analysis of results provided insurance to the overall research effort in validating the physical theory, confirming cell performance, and establishing the credibility of the research team. EPRI has been extremely fortunate to have as a part of its management process a cadre of key advisers, whose experience and insight have proved indispensable in the direction and modification of research approaches.

So much for the past. With success has come a whole new set of challenges in transferring accomplishments from the laboratory to the manufacturing environment and then to the field. The next major step, demonstrating the manufacturability of the point-contact device, is well under way at Acrian, Inc., a San Jose, California, semiconductor firm. Four utilities—Arizona Public Service Co., Georgia Power Co., Pacific Gas and Electric Co., and Southern California Edison Co.—are determined that the industry will not have to trust to luck in this critical stage.

By providing funds to the project above and beyond annual contributions to EPRI, these utilities are cosponsoring the effort to demonstrate utility integration of advanced photovoltaic systems. In addition, they will participate in the performance evaluations and demonstration of early modules and arrays based on the point-contact cell. If technical and economic successes continue, these utilities will be preferentially positioned, from a business standpoint, to participate in the commercialization of a revolutionary new power technology.

John E. Cummings, Director
Renewable Resources Systems Department
Advanced Power Systems Division

Authors and Articles


DeMeo


Narita


Mueller


Parris

Opening the Door for Utility Photovoltaics (page 4) reviews manufacturing process R&D to transform a 10-year solar cell research effort into a bulk power technology that will prove efficient enough for utility use. Written by Taylor Moore, *Journal* senior feature writer, with assistance from two research managers of EPRI's Advanced Power Systems Division.

Edgar DeMeo, manager of the Solar Power Systems Program, has guided EPRI research in photovoltaics, solar-thermal, and wind energy technologies for seven years. He came to the Institute in 1976 after six years on the engineering research faculty at Brown University and two years as an instructor at the U.S. Naval Academy. An electrical engineering graduate of Rensselaer Polytechnic University, DeMeo later earned an MS and a PhD at Brown.

John Cummings, director of the Renewable Resources Systems Department since 1979, joined EPRI as a project manager in 1975 and headed EPRI's solar energy research from 1976 until 1979. He formerly was director of energy programs for Itek Corp. and, still earlier, was a technical analyst with the Atomic Energy Commmission. Cummings graduated in engineering from the Coast Guard Academy. He later earned an MS and a PhD in physics and an MBA at the University of Arizona. ■

Economics and Energy in 21st-Century Japan (page 16) summarizes major trends that are expected to shape Japan's electricity consumption and its R&D on generation and delivery technologies during the next 25 years. Written by **Hiroshi Narita,** president of Japan's Central Research Institute of Electric Power Industry.

Narita has been president of CRIEPI since 1981, following 30 years with Tokyo Electric Power Co., where he became executive vice president. He also presides over specialized research associations for combustion turbines and heat pumps, and he is president of the Japan International Electric Research Exchange Council. Narita graduated in law from Tohoku Imperial University. ■

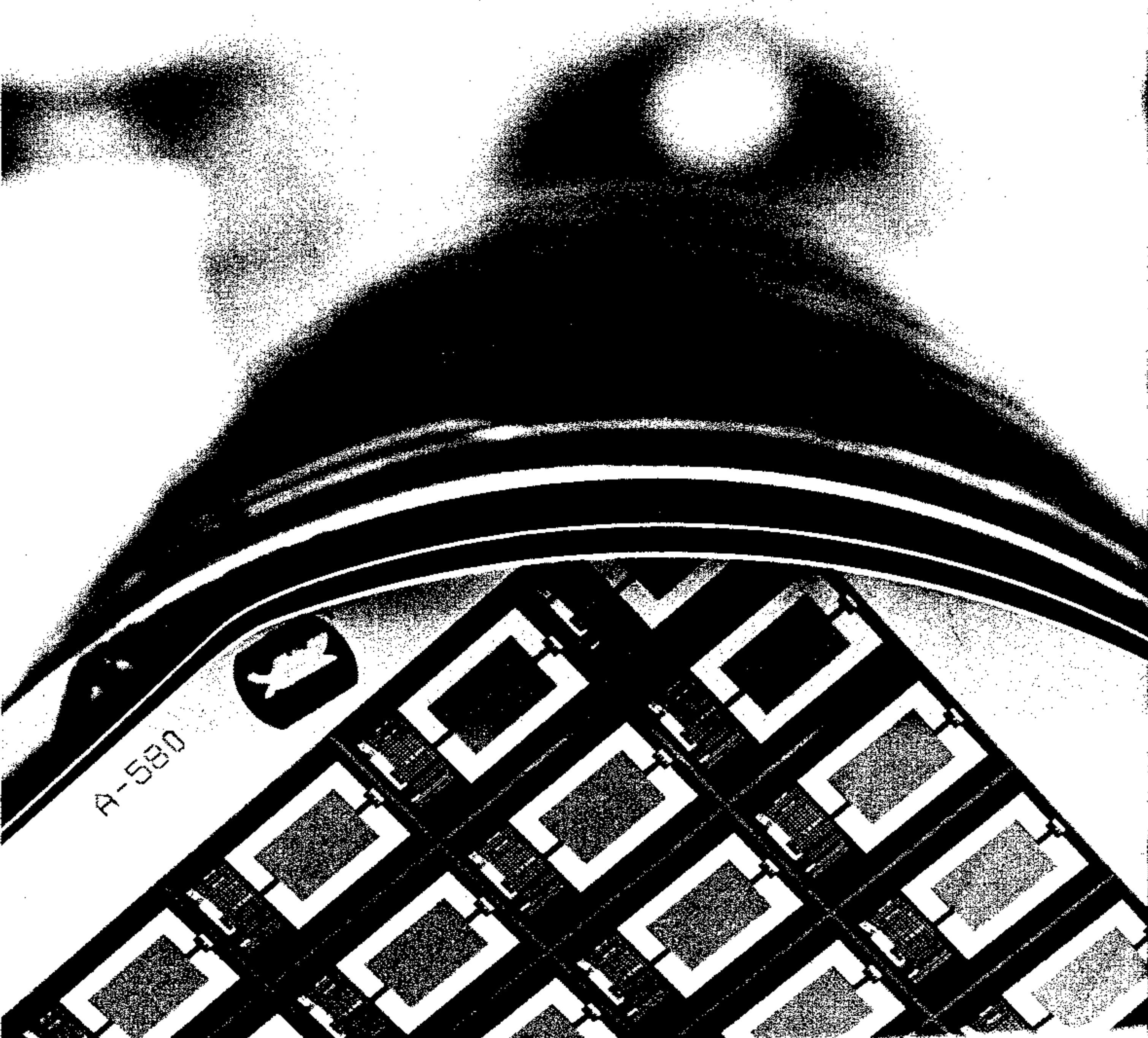
A Clear Challenge in Visibility Research (page 20) explains the major factors that impair visual air quality and describes new monitoring programs for learning what is necessary to keep the atmosphere invisible. Written by Taylor Moore, senior feature writer, aided by staff of the Environment Division.

Peter Mueller is a subprogram manager for air quality studies, with a particular interest in precipitation chemistry. He has been with EPRI since 1980, following 7 years with Environmental Research & Technology, Inc., where he was manager of an environmental chemistry center. Briefly with the EPA before that, Mueller had worked for 16 years with the California Department of Health, becoming director of its air and industrial hygiene laboratory. He received a BS in chemistry from George Washington University and an MS and a PhD in environmental science from Rutgers University. ■

Speeding Transfer of Nuclear Maintenance Technology (page 30) describes an EPRI-sponsored center that demonstrates and encourages new techniques in nuclear power plant maintenance. Written by Jon Cohen, science writer, with cooperation from staff of EPRI's Nuclear Power Division and one of its R&D contractors.

Howard Parris, program manager for human factors research, has been with EPRI since 1979. Before that he worked for the Air Force Human Resources Laboratory in Texas for 7 years. Earlier, Parris managed human factors engineering for Lockheed Georgia Co. for 7 years, following a 22-year military career in the Air Force. He earned an MA and a PhD in industrial psychology at the University of Southern California and Ohio State University, respectively.

Kenneth Brittain of J. A. Jones Applied Research Co., Charlotte, North Carolina, manages the Maintenance Equipment Application Center for EPRI. ■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EPRI's point-contact photovoltaic cell has achieved the world's highest conversion efficiencies in a laboratory environment. But can such devices be economically mass-produced for utility-scale applications? Researchers, microcircuit manufacturers, and utility investors are betting that they can.

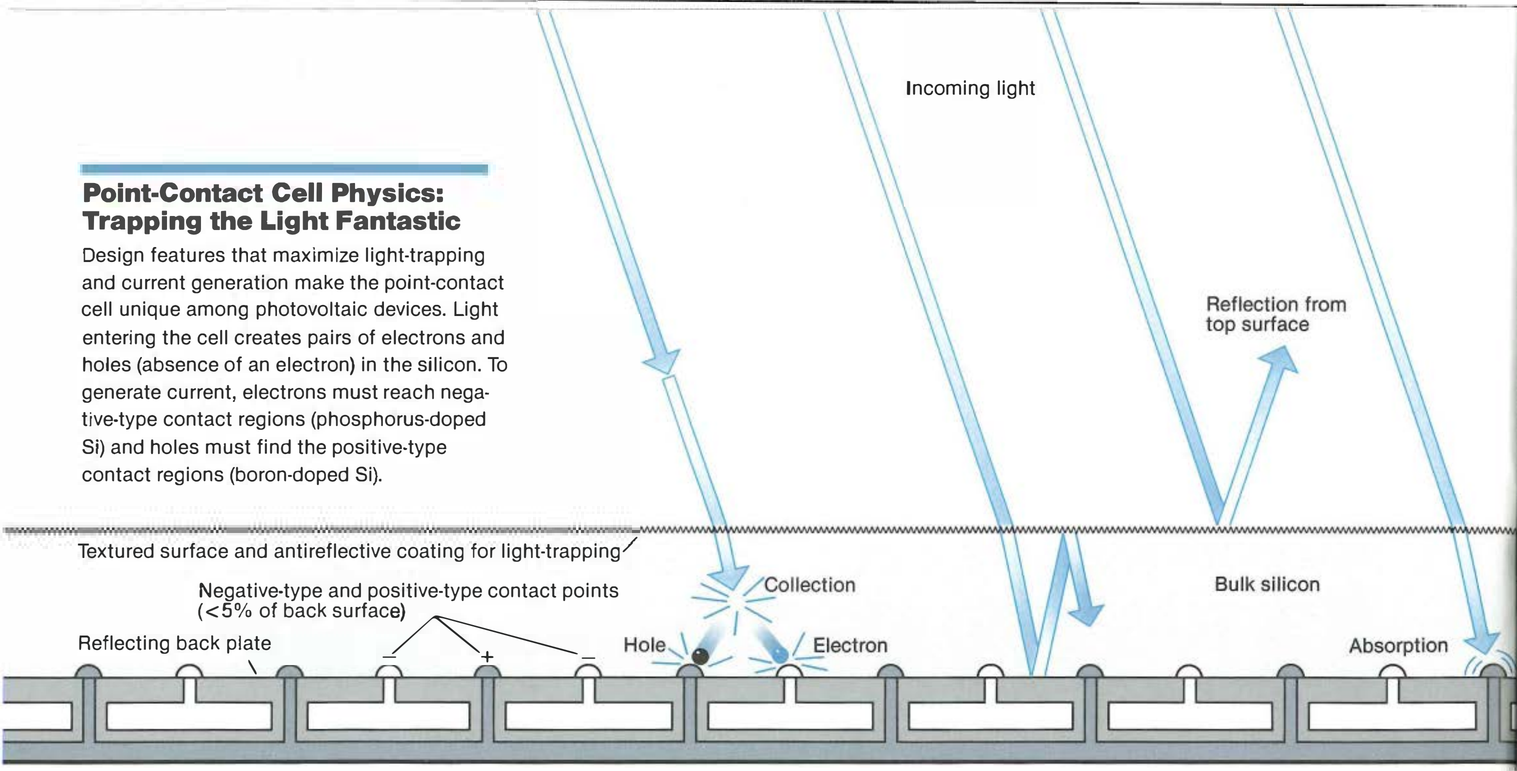
OPENING THE DOOR for UTILITY PHOTOVOLTAICS

In the clean rooms of a Silicon Valley microelectronics maker, operators are preparing trial batches of a revolutionary kind of silicon chip—one that turns the searing light of 500 suns into about 6 W of electric power at a cost that may rival conventionally produced electricity in the next decade. For the solid-state electronics industry, accustomed to setting new milestones in the power packed into fingernail-size microcircuits, the challenges posed in making solar cells seem similar, almost routine.

Yet the solar cell emerging from the silicon wafer diffusion furnaces took nearly a decade to travel the R&D path from the Stanford University electronics laboratories where it was designed to the clean-room manufacturing facility only 20 miles down the road. So far, about $8 million has been invested to develop the cell, which currently holds the world record in photovoltaic (sunlight-to-electricity) conversion efficiency. As have many other pioneering electronic innovations born at the Stanford laboratories, the solar cell has occupied the talent and energy of a team of researchers over the years. And it may require another $15 million to

Point-Contact Cell Physics: Trapping the Light Fantastic

Design features that maximize light-trapping and current generation make the point-contact cell unique among photovoltaic devices. Light entering the cell creates pairs of electrons and holes (absence of an electron) in the silicon. To generate current, electrons must reach negative-type contact regions (phosphorus-doped Si) and holes must find the positive-type contact regions (boron-doped Si).



$20 million to demonstrate commercially viable mass production and to confirm full module performance at the megawatt scale needed for utility bulk power generation.

For EPRI, sponsor of the work both at Stanford and in Silicon Valley, as well as at other firms, the cell is a triumph of research and development. To be sure, there remain many hurdles on the road to a commercial, utility-grade product. Still, research managers are confident that the device they call the point-contact photovoltaic cell could be generating significant amounts of electric power in the 1990s for utilities in the nation's Sunbelt.

The sun on a silicon chip

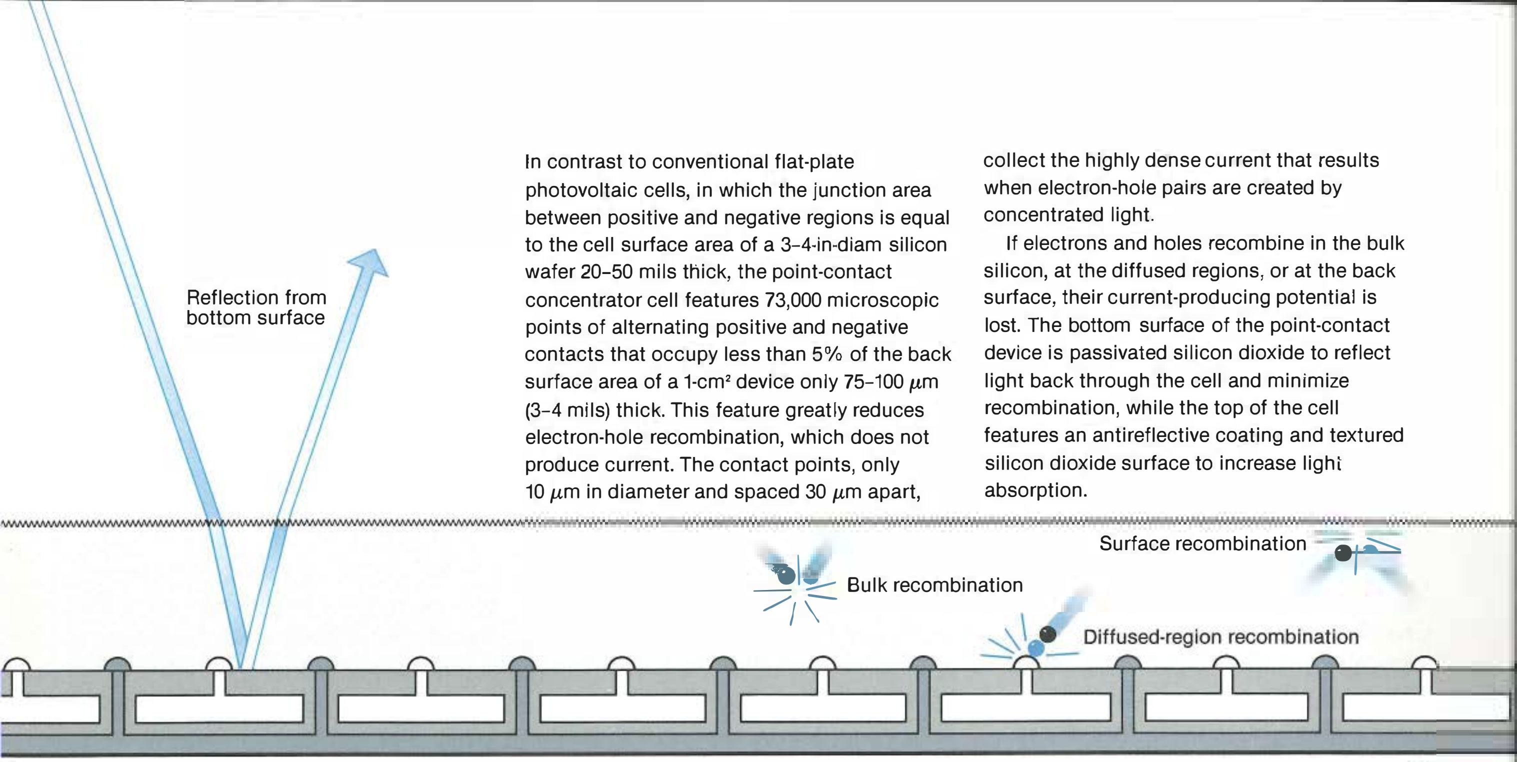
Photovoltaic technology will give utilities in areas with good solar resources a modular, emissions-free, solid-state generating option. Capable of being built quickly in stages, photovoltaic systems have few moving parts, and on the basis of performance monitoring of small-scale utility-connected demonstrations already operating, they are expected to have very low operating and maintenance costs. Moreover, monitoring data from existing conventional photovoltaic systems in the Southwest indicate that their sun-powered energy output matches well with utilities' peak daily load curves.

"It is exciting to consider where we are today with this cell and where the performance of photovoltaic systems using this cell is expected to be in a few more years. Ten years ago we knew that we would need a solar cell with very high efficiency for utilities to make economical use of photovoltaic power, and we are approaching the point where the high-efficiency cells can be mass-produced," says Dwain Spencer, EPRI vice president and director of the Advanced Power Systems Division.

Spencer came from the California Institute of Technology's Jet Propulsion Laboratory in 1974 to set up a solar research program for EPRI. He has seen the effort mature from early investigations of a bewildering array of photovoltaic concepts and devices to the showcase concentrator cell that has achieved unprecedented 28.2% efficiency in the laboratory and is approaching pilot-scale manufacture under EPRI contract at Acrian, Inc.'s San Jose, California, plant.

John Cummings, department director for renewable resources systems, and Edgar DeMeo, program manager for solar power systems, who are now responsible for the research management, know equally well the significance of the accomplishment with the concentrator cell. "This is a device that from the start was designed to meet utility requirements for photovoltaic power generation, and it really looks promising as a future option for utilities," observes Cummings. "It was the continuity of the R&D support from EPRI and the utility industry that made it possible. Now we're approaching the demonstration phase of the research, development, and demonstration process."

Adds DeMeo, "We are at a critical juncture. The work at Stanford has proved that a high-efficiency silicon cell can be made. We still have to deter-



In contrast to conventional flat-plate photovoltaic cells, in which the junction area between positive and negative regions is equal to the cell surface area of a 3-4-in-diam silicon wafer 20–50 mils thick, the point-contact concentrator cell features 73,000 microscopic points of alternating positive and negative contacts that occupy less than 5% of the back surface area of a 1-cm² device only 75–100 μm (3–4 mils) thick. This feature greatly reduces electron-hole recombination, which does not produce current. The contact points, only 10 μm in diameter and spaced 30 μm apart, collect the highly dense current that results when electron-hole pairs are created by concentrated light.

If electrons and holes recombine in the bulk silicon, at the diffused regions, or at the back surface, their current-producing potential is lost. The bottom surface of the point-contact device is passivated silicon dioxide to reflect light back through the cell and minimize recombination, while the top of the cell features an antireflective coating and textured silicon dioxide surface to increase light absorption.

mine if it can be made by the millions like integrated circuits at a cost comparable to that of circuit chips and still have high efficiency."

Although there are thousands of nonconcentrating flat-plate photovoltaic cells in use today in a wide range of remote power and consumer electronics applications, as well as in a few megawatt-scale central station generating facilities, none of them produces power at a cost that competes with fossil fuels. Most of the cells are of such low efficiency (well under 15%) that the area-related costs (e.g., for modules, tracking and support structures, land, and installation) of deploying them in large numbers for bulk power overwhelm the economies achievable by installing them in multimegawatt increments.

Much of the estimated $1.5 billion in photovoltaic research over the past 10 years funded by EPRI, DOE, and industry has aimed at increasing basic cell efficiency through design or materials improvements and by optical concentration of sunlight to reduce the size of the cell that must be exposed to sunlight and, in turn, lowering the area-related cost of power.

CONCENTRATING SUNLIGHT geometrically 100 or more times with a Fresnel lens or parabolic mirror onto small but highly efficient solar cells provides the leverage necessary to counterbalance the area-related cost curve. Although modules containing such cells require precise tracking of the sun to maintain the intense beams, their greater efficiency and up to 10-fold greater power output per cell make them an especially attractive option for bulk electricity generation. Moreover, concentrator photovoltaic technology is believed likely to precede the commercial availability of advanced flat-plate crystalline cells or high-efficiency amorphous thin-films—photovoltaic technologies that also show promise for utility application.

"The advantage of going with a concentrating photovoltaic system for utility use is that more effort can be devoted to maximizing the performance of the cells through the sophisticated processing techniques of metallization and dopant diffusion used in making microcircuits. The expected result is that the cells, although they are fairly expensive on an area basis, don't account for such a major fraction of the total system cost," explains Cummings.

Two semiconductor materials (single-crystal silicon found in conventional photovoltaic cells and the more exotic and expensive gallium-arsenide being pursued for a wide range of electronic applications) have shown the most promise of yielding high photovoltaic efficiency under concentrated sunlight. Federally funded research at Sandia National Laboratories and Varian Associates has achieved 25–26% efficiency in gallium-arsenide cells under 700–1000× concentration. Silicon cells, believed to be more readily and cheaply manufacturable because of the lower cost of silicon and its compatibility with standard integrated-circuit processing techniques, have been the focus of EPRI's concentrator cell program at Stanford, where steady successes in recent years have led to 28.2% efficiency at 110× concentration in the laboratory.

After a decade of relentless R&D, both materials have achieved the efficiencies judged essential for generating power at a target cost of 6–8¢/kWh in the 1990s (constant 1986 $). But key questions that remain for both are whether the cells can actually be manufactured for about 20¢ per peak watt of rating and whether they can be made to last for the 20–30 years typical in traditional utility life-cycle economic analyses of alternative power technologies. For the silicon concentrator cell, EPRI is committed to finding out.

One path leads to another

The solar cell work at Stanford began in 1976 but with a different kind of cell in mind than the type that has since made headlines around the world with its record efficiency. Richard Swanson, an associate professor of electrical engineering who leads the team that eventually designed the concentrator cell, explains that researchers initially thought the path to high performance would be a thermophotovoltaic (TPV) cell. In this approach, extremely concentrated sunlight (>10,000×) from a large 33-ft-diam (10-m-diam) parabolic dish mirror heats a refractory material to an incandescent 3500°F (1927°C); that radiation can then be converted to electricity by a silicon cell at a higher theoretical efficiency (40%) than is possible in a conventional cell.

"We knew the efficiency of the cell had to be pretty high because that's the only real leverage you have in the system. You have to get enough energy out to pay for all the rest of the system that concentrates light on the apparatus," explains Swanson. He and his colleagues managed to push efficiency in one experimental TPV cell as high as 30%, compared with about 7% when the research began.

But by 1982 and with the help of a powerful three-dimensional computer model of the cell physics that allowed researchers to optimize the movement of electrons in the 100-μm-thin silicon, Swanson concluded that the TPV cell's performance resulted more from its good electrical characteristics than from the anticipated TPV effect. Calculations indicated the cell would have about 23% efficiency under moderate concentration of sunlight. That led the team to focus on a purely photovoltaic cell optimized for about 500× direct concentration.

"In the course of our work on the TPV converter, we learned a lot about what makes solar cells work and improved on the basic science of photovoltaic energy conversion. It forced us to throw away the slate and start from scratch. We gained a new perspective on the devices and what is the best way to build the most efficient cell," recalls Swanson, who was first introduced to EPRI through John Linvill, a former chairman of Stanford's electrical engineering department and an acquaintance of Chauncey Starr, EPRI's founding president and vice chairman.

THE RESULT OF THROWING AWAY THE SLATE and starting from scratch is the point-contact cell, unique among photovoltaic devices in several ways. For one, the positive and negative contacts are in some 73,000 microscropic points on a tiny piece of silicon that is only 0.8 cm (0.3 in) on a side in active area, 1 cm^2 (0.155 in^2) in total area. In the point-contact design chosen for manufacturing development, the *p* and *n* contact points are all on the back of the cell, with no metal grid on the top surface. For conventional flat-plate cells, junctions between *p* and *n* material regions are formed in entire 3–4-in-diam (75–100-mm-diam) silicon wafers by the diffusion of dopant impurities (typically boron-silicate for the positive junctions and phosphorus-silicate for the negative junctions).

Another unique feature is the point-contact cell's trapping of light photons through the combined effects of surface texturing on the top of the cell for greater absorption of incoming rays and a reflecting back plate that, as Swanson explains, "allows the light to sort of rattle around in the silicon until it eventually knocks an electron loose." This characteristic, exploitable thanks to the detailed cell analytic model, means that the cell absorbs more sunlight.

"In a conventional cell the current moves in much the same direction: top to bottom. But in the point-contact cell it moves in a complicated path, hopping from positive to negative dots on the bottom in a sort of swirl pattern," Swanson adds. He says 30% laboratory cell efficiency—just under the 32.3% theoretical limit for silicon cells—is possible in another one or two years, "but it requires getting everything absolutely right.

"Building photovoltaic devices is like carrying peas on a knife: one little thing wrong and the peas want to fall off. With this cell, one wrong step and the current doesn't want to come out as electricity; it wants to come out as waste heat," Swanson explains.

Indeed, an important design concern with the point-contact cell is dissipating about 18 W (th) of waste heat from concentrated light that is not converted to current. The cell's operating temperature must be held at about 140°F (60°C) to maintain high efficiency, so researchers have designed a passive-cooling copper heat-spreader that would be manufactured as part of the bottom plate of the cell housing to transfer waste heat outside the module assembly.

A major focus both in the design and now in the initial stages of manufacturing the point-contact cell for high efficiency is to increase the time, measured in millionths of a second, available for negative charge carriers (electrons) and positive charge carriers (holes) to reach the contact points before they recombine or lose their ability to contribute to useful current.

In the laboratory this minority carrier lifetime has been pushed to several hundred microseconds in quarter-scale cells; researchers believe full-scale cells must maintain carrier lifetimes of 300 μs or better. That could translate to a manufacturing requirement of carrier lifetime as high as 1000 μs (1 ms) in the starting silicon because lifetimes degrade during wafer processing steps.

Swanson is convinced the point-contact cell is "an eminently manufacturable device" regardless of the degree of further optimization that can be achieved in the laboratory. "Mass-producing this device is a given; it can be done. That's not to say it's a trivial task, but it will not be a show-stopper. It was designed from the start to be manufactured with standard integrated-circuit processing techniques," adds Swanson, and that is precisely what Acrian is under contract to EPRI to demonstrate.

Reflecting on the accomplishment with the cell at Stanford brings a seemingly melancholy note to Swanson's voice, now that (in a sense) the baby has been sent off to school at Acrian's wafer and semiconductor device fabrication plant. "One of the most important factors in our success was the long, stable funding base that EPRI provided. It allowed us to build a team of people (over a dozen at one point) with special expertise. It was the group dynamic

Advanced Materials for Advanced Semiconductors

Materials quality concerns loom larger as R&D approaches the theoretical performance limits of such semiconductor devices as concentrating solar cells, very large-scale integrated circuits, and other power electronics. EPRI has begun initial funding of a state-of-the-art semiconductor materials characterization program at the Georgia Institute of Technology to support commercial development of the Advanced Power Systems (APS) Division's point-contact solar cell, but the research scope is also being broadened to address advanced semiconductor materials requirements related to R&D in other EPRI divisions. This includes work sponsored by the Electrical Systems (ES) Division on power semiconductors for utility transmission systems, as well as industrial power electronics applications being pursued by the Energy Management and Utilization Division.

With funding and support from many sources, Georgia Tech (already a national leader in some areas of semiconductor research) is assembling the Microelectronics Research Center in Atlanta. The institute has proposed to EPRI the establishment of a program within the center that could offer wide-ranging basic research and materials characterization capabilities of benefit to all EPRI semiconductor device development efforts.

Some of the materials requirements for the concentrating solar cell may be met through ongoing work sponsored by the ES Division on advanced crystal growth technologies. Similar criteria for both high-performance solar cells and power semiconductors include extremely high purity, very low crystal defects, and high electrical resistivity. But there are some important differences. Advanced power semiconductors need charge carrier lifetimes of 100 μs or less in bulk silicon, while point-contact solar cells must have carrier lifetimes at least as high as 300 μs. Wafers of 4 in diam (10 cm diam) are probably adequate for power semiconductors, but minimizing production costs for solar cells ultimately demands using 6-in (15-cm) or larger wafers.

Such dimensions and purity requirements cannot now be achieved with domestically produced Czochralski silicon but require the more expensive float-zone method or a suitable alternative. The ES Division sponsors work by Westinghouse Electric Corp. that is exploring ways to reduce the cost of float-zone silicon, as well as research by other contractors on such alternatives as magnetically grown crystals.

Frank Goodman, an APS Division solar power systems project manager, explains that the beginning focus at Georgia Tech for the point-contact cell will be to assess starting material quality in much greater detail than before and to evaluate the influence of high-temperature processing during cell manufacturing. "We hope to make some great strides in the fundamental understanding of existing material quality and the influence of processing that will benefit both the photovoltaic cell and power semiconductor applications within a couple of years."

The work will involve advanced techniques and technologies, such as deep-level transient spectroscopy, photoluminescence and photoconductivity analysis, positron annihilation, and Fourier-transformed infrared spectroscopy. EPRI will provide test samples of point-contact cell wafers at different stages of processing from Acrian and other sources. □

From Cells to Arrays: Packaging the Concentrator

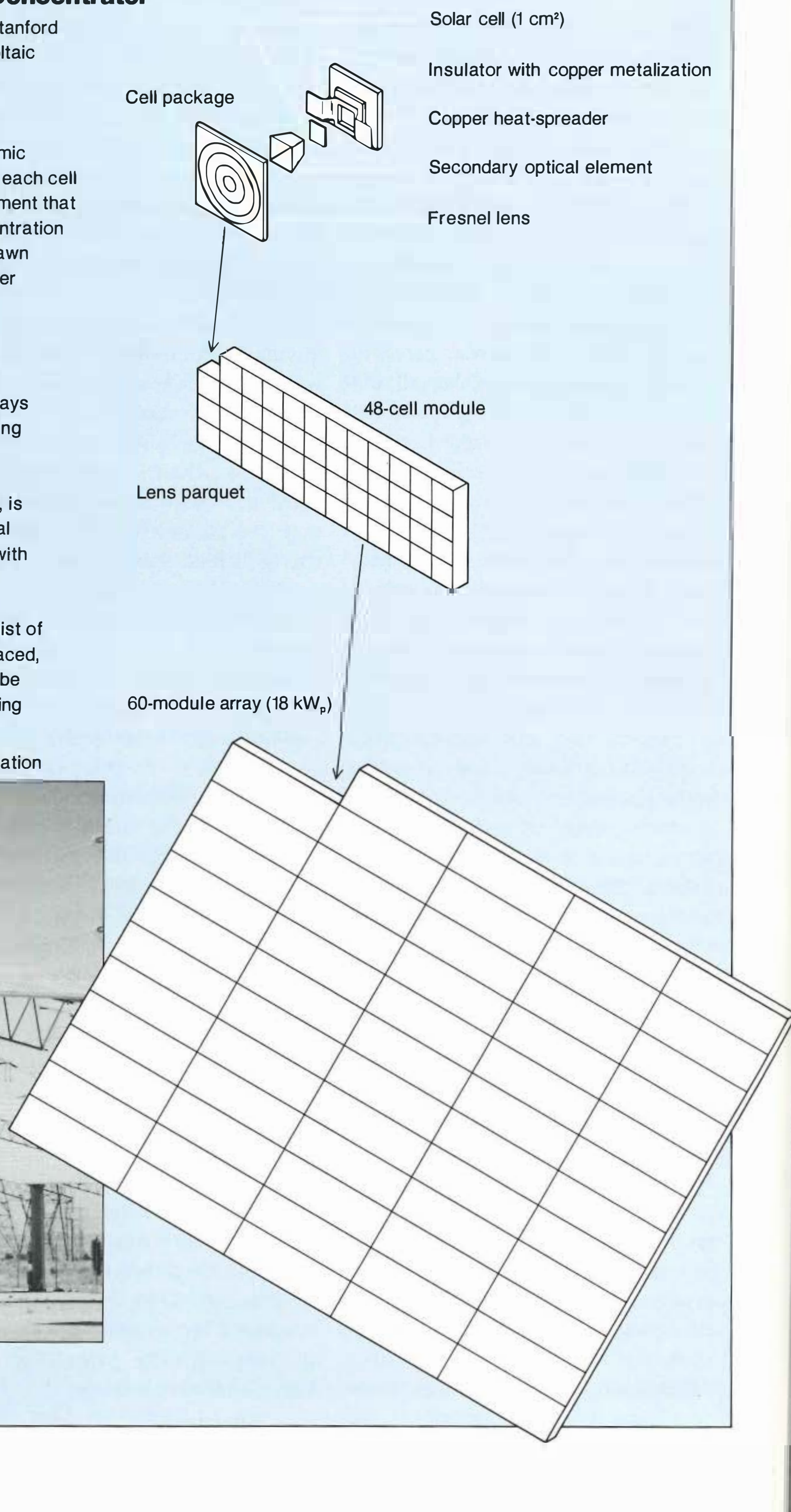
Designs are being developed for integrating the EPRI–Stanford University concentrator solar cell into full-scale photovoltaic arrays for testing and demonstration.

After manufacture by semiconductor device fabrication processes, each point-contact cell is soldered to a ceramic insulator that is direct-bonded to copper contacts. Atop each cell is bonded a reflecting aluminized secondary optical element that helps a Fresnel lens above it to maintain 500-sun concentration on the cell surface. Mounted in the bottom of a deep-drawn module housing, each cell is in turn mounted on a copper heat-spreader bonded to the inside of the module.

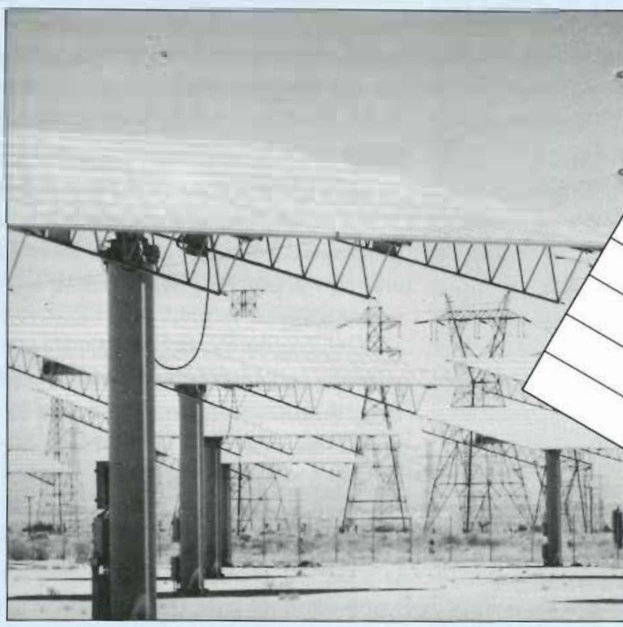
The 48-cell module, an aluminized steel pan measuring 29 x 87 in (750 x 2210 mm) and covered by a parquet of Fresnel lenses, becomes the building block for large arrays comprising 60 modules and having a peak electrical rating of about 18 kW.

The concentrator array, nominally 100 m² (about 1000 ft²), is mounted on a 14-ft (4-m) pedestal that provides structural support and keeps it optimally pointed toward the sun with a computer-controlled, electronic drive-tracking system.

A 100-MW central station generating facility would consist of about 5600 such 18-kW arrays, which, when properly spaced, could occupy over 600 acres (240 ha). The facility could be constructed in 10-MW increments as additional generating capacity is needed.



Central station



that got everybody excited about the cell, rowing in the same direction and thinking about it hard enough to overcome the problems. I think EPRI understood that, as evidenced by its support of our team, but I think that spirit and dynamic could be just as important in actually commercializing the cell."

Down in the Valley

Such a team spirit is rapidly coalescing at Acrian's 65,000-ft^2 (6040-m^2) manufacturing plant in San Jose. Founded in 1978, the $22-million-a-year Silicon Valley firm supplies thousands of radio frequency and microwave power transistors and amplifiers for a host of military and commercial avionics, radar, and communications equipment. Many of these devices, similar in fundamental design to the point-contact cell, are made for only a few dollars each through high-volume production. EPRI has equipped the Acrian plant with enough additional wafer-processing and chip-manufacturing equipment to determine (perhaps by 1988) whether the solar cells can be made in comparable volume and at comparable cost.

"There were enough similarities in the technologies and in the way we do business—bringing technology from the laboratory to a manufactured product—that there seemed a good fit between Acrian and EPRI," says Jack Harris, company chairman and CEO, who adds that Acrian has a long-range eye on becoming a worldwide supplier of point-contact cells if they can be commercialized.

"From our perspective, the point-contact cell is a perfect application for silicon because as the production volume goes up and if demand for the cells is there, the price will come down. We see the development effort with EPRI as a good business opportunity because there could be significant market demand, almost irrespective of the cost of oil, if the cells can be made for about $1 apiece."

The manufacturing challenge also interested Acrian because of the similarities to the microwave semiconductor business. "One of the principal problems with power semiconductors is dissipating heat; one of the problems with solar cells is dissipating heat," notes William Ruehle, Acrian's senior vice president. "We're accustomed to working with very thin, fragile wafers on the order of a few hundred micrometers, although the point-contact cells will be four or five times thinner. Plus, for both technologies you need ultraclean manufacturing environments able to process wafers with an absolute minimum of contaminants.

"We do all our own device fabrication here. So there's a good interchange of technology," continues Ruehle. "We're building from a technology base that already exists. We've set up a separate team and production area dedicated to the solar project, attempting to duplicate the cell developed at Stanford in a high-yield manufacturing environment. Over the course of the next year or so the goals are to do that and to approach the levels of efficiency that Professor Swanson has proved are feasible."

Keys to achieving high yield revolve around the extraordinary measures required to battle the twin demons of the microchip industry: breakage and contamination. Limiting breakage of the delicate slices of silicon pushes manufacture toward process automation that ideally eliminates direct human touch from all steps between the bare wafer and the final metallized cell circuits. Automation would also reduce the possibilities for contamination of the wafer surfaces by air- or human-borne particles. Chemicals from particles or any metals that touch the wafers diffuse into the silicon during high-temperature (>2000°F; 1100°C) processing. Contamination is also a concern with respect to the parts-per-million levels of oxygen in the basic silicon that result from the way the crystal is grown. Irregularities in the crystalline structure itself, particularly at edges or surfaces, can also render useless an otherwise powerful microcircuit or destroy the efficiency of a concentrator cell.

ALSO IMPORTANT, BUT PERHAPS NOT CRUCIAL, for high yield and low cost is the size of the wafers. Single conventional flat-plate photovoltaic cells are made from individual wafers of 3–4 in diam (75–100 mm diam), but a 3-in wafer processed into concentrator cells yields about thirty-six 1-cm^2 (0.155-in^2) cells in a cookie-cutter-like grid. Increasing the size of the wafers and, by implication, the diameter of the silicon ingots from which they are cut dramatically boosts the number of cells producible from a single wafer. A 5-in (125-mm) wafer, for example, could yield over 100 cells, while an 8-in (200-mm) disk might have nearly 300 cells packed on it. But such a leap in wafer dimensions awaits continuing advances in basic silicon production technology that is driven by requirements of the integrated-circuit industry.

Walter Lamb, Acrian's solar wafer fabrication manager, notes that premium-priced silicon made by the float-zone process is required for meeting the purity and size requirements for high-efficiency concentrator cells. Simple semiconductor devices and flat-plate photovoltaic cells are made from silicon produced by the more familiar, less expensive Czochralski process in which a single-crystal ingot is pulled from a molten vat of silicon. But that process introduces seemingly unavoidable impurities into the silicon from the crucible itself. On the other hand, there are only three producers of hyperpure float-zone silicon in the world, and none is domestic (one is in West Germany and two are in Japan).

"To maintain high bulk carrier lifetimes through all processing stages requires either float-zone silicon or a much improved alternative to Czochralski silicon," explains Lamb. "After some period of prototype production and testing, we'll need lots of the material in the future."

"We're pushing the state of the art of what's out there now, but not so far that we can't get it," adds Harris. "We're working with 4-in wafers now for the point-contact cell. Eventually, in full-scale production we'd like to be using 8-in or larger. The integrated-circuit business is struggling with 6-in and talking 8-in, and in another three years it may be there. We hope to piggyback on the progress being made in the semiconductor industry. They say the typical size of a wafer goes up an inch every two years. Yet we might still get a reasonable cell price on 5-in wafers, which are here today.

"By the time we get into full-scale production the materials requirements Walter talks about may be the mainstream for this type of product—it's more than likely, given a progression of successes. If by that time the capabilities of the semiconductor industry are even higher, then we'll take advantage of it, but so far wafer size does not seem to be a barrier to duplicating Stanford's success today, nor does it seem a concern for success over the long term. The volume demand for semiconductors will dictate to industry what is needed and the industry will respond to the requirement."

Meantime, the pace is quickening inside Acrian's solar cell fabrication area as engineers and technicians prepare to jump from the quarter-scale cells they have been making for equipment shakeout and process testing to full-size circuits with metallized electrical contacts. "The first-run cells were very successful from the point of view of equipment qualification and process definition," says Mary Bernstein, an Acrian staffer who is coordinating the EPRI project. "It showed us we have a good understanding of what's required and convinced us we can build on that understanding to develop the full-scale cell."

"By the end of this year we hope to be producing cells with target efficiencies as high as 24%," reports Bernstein. "The 1988 focus will be on boosting cell efficiency further, reducing production costs, and trying to automate the whole process." That year could also be the critical one for bringing together many of the other components (including cell mounting, lens, and module housing)—components for which EPRI has parallel projects in progress—that will make up a complete photovoltaic concentrator array.

Putting it all together

By 1988 EPRI hopes to have a sufficient number of cells from Acrian's production line to build a few 18-kW arrays for testing, further development, and demonstration. Within another year or so from then, the plan calls for three or four utility-cosponsored prototype central station demonstrations, each 100–300 kW in peak rating. To get there, most of the other elements in addition to the cell must soon be in hand or nearly so. DeMeo, the solar power systems program manager, says that work is progressing at a fast clip on aspects such as the cell's Fresnel lens, reflecting aluminum secondary optical element, module design, and overall balance of system design.

The Kansas City, Missouri, firm of Black & Veatch Engineers-Architects has been EPRI's prime contractor for the concentrator module design. General Electric Co. and Martin Marietta Denver Aerospace Co., both of which bring experience from the DOE-Sandia concentrator program, have contributed supporting work as B&V subcontractors. Working in recent years in parallel with Swanson at Stanford, B&V has refined the module design as cell efficiencies climbed and electrical and mechanical requirements became clearer.

The completed, but still tentative, engineering design calls for an aluminized-steel housing containing 48 cell packages in a 4-row, 12-column matrix covered by two parquets, or groups, of Fresnel lenses of 24 elements each. Each of the lenses measures 178×178 mm (7×7 in). Each cell package beneath a lens includes the secondary optical element mounted on top to help maintain the point focus on the cell, which is soldered to a direct-bonded copper alumina substrate and (beneath that) to a copper heat-spreader. A module would also contain six bypass diodes (to prevent reverse flow of current among the cells), each wired in parallel with two 4-cell series strings.

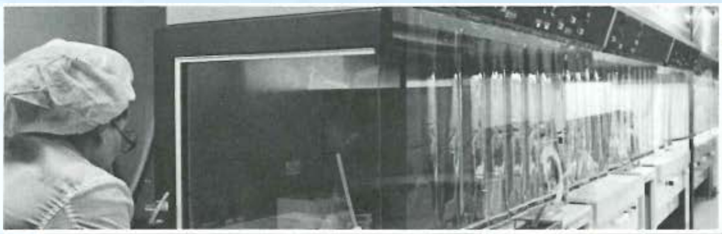
Such a 48-cell module would have a peak power rating of 287 W and an efficiency of 22%, using a 27.5%-efficient point-contact cell (optical losses between the lens and cell and wiring losses account for the difference). At large production rates, B&V estimates the cost of the complete module, including the cell, at $275, or 96¢ per peak watt.

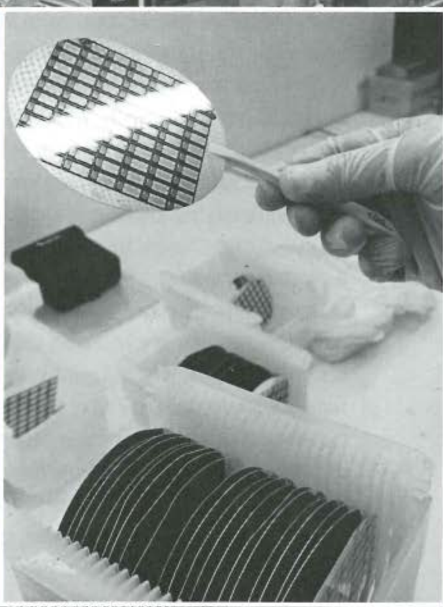
EPRI has contracted with Cummings Engineering, Inc., of Wilmington, Massachusetts, for detailed construction specifications and production of prototype modules. The firm (no relation to John Cummings) is expected to deliver 10 modules by next year to complete initial testing. Another 200 could be integrated in arrays for performance analysis. Somewhere on the order of 3000 production models could be ordered after that for utility-hosted demonstrations.

A conceptual design by B&V of an 18-kW, two-axis tracking array consist-

Silicon Valley, Sunny-side Up

The EPRI-funded point-contact cell developed at Stanford University is entering prototype production at Acrian, Inc., in San Jose, California. The Silicon Valley firm produces semiconductor power transistors and amplifiers for a variety of applications, and manufacture of the solar cell has many similarities to the firm's established products. Acrian's plant has been equipped with an additional, dedicated wafer-processing line to determine whether the point-contact cell can be mass-produced at the low cost achieved with power semiconductors. Although quarter-scale cells made in the Stanford laboratory have achieved better than 28% photovoltaic efficiency, Acrian's goal is to produce full-scale cells with efficiencies as high as 24% by the end of this year. Efforts to boost efficiency still further and to automate the production process would follow.



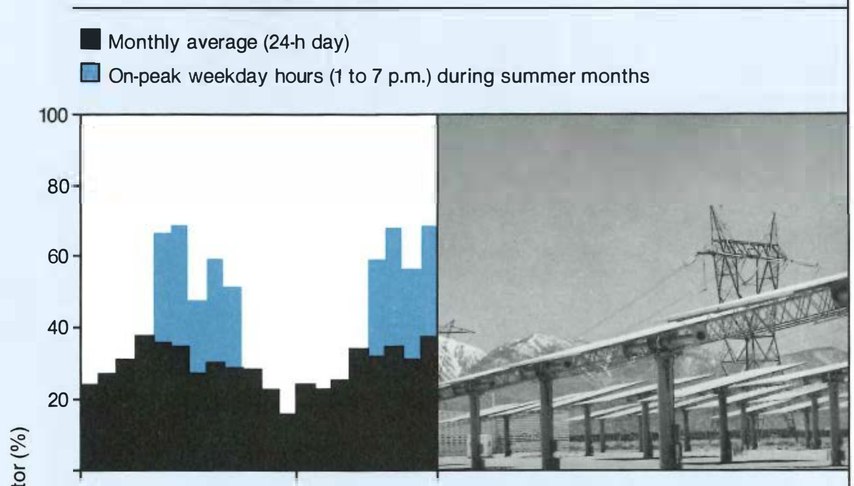


Central Station Photovoltaic Plant Performance

Recent performance data for two Arco Solar, Inc., central station photovoltaic power plants in California that employ present-generation flat-plate cells indicate monthly average (based on 24-h day) and summer peak-hour capacity factors that bode well for future plants using more-efficient advanced flat-plate or concentrating solar cells. The Lugo facility, nominally rated 1-MW (850-kW at standard operating conditions), supplies power to the Southern California Edison Co. system near Hesperia in the San Bernardino Mountains. The Carrisa Plains site, east of San Luis Obispo in central California, is nominally 6.4 MW (5.2 MW at standard operating conditions) and is connected to the Pacific Gas and Electric Co. system. Data were recorded and analyzed by the respective utilities jointly with Arco Solar.

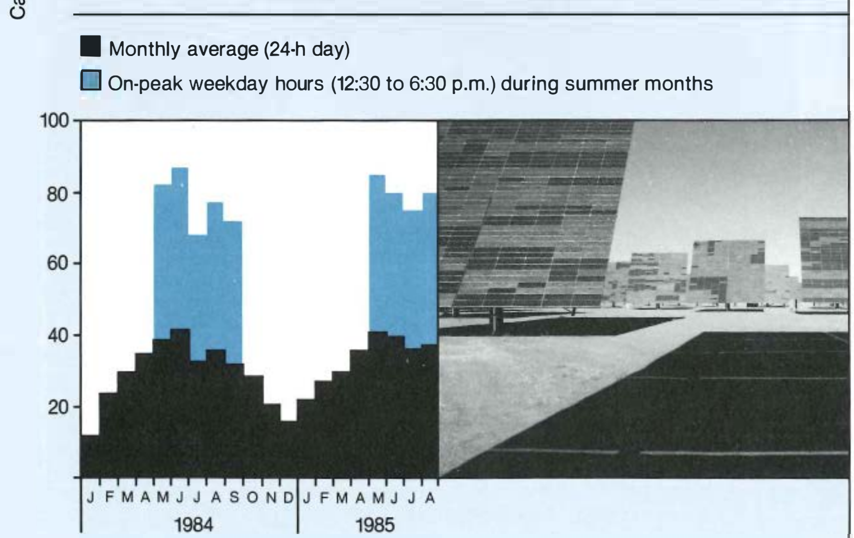
Lugo Capacity Factors

(nominally 1 MW; 850 kW at standard operating conditions)



Carrisa Plains Capacity Factors

(nominally 6.4 MW; 5.2 MW at standard operating conditions)



ing of 60 concentrator modules (2880 cells) has been in hand for several years and is now being refined. It incorporates concepts developed by General Electric for lens, secondary optical element, and cell packaging, as well as Martin Marietta's design for array structure and tracking drive system. Martin Marietta designed a 225-kW concentrator array at Phoenix Sky Harbor Airport that was funded by DOE and has been operated by Arizona Public Service Co. since 1982. Many features of the EPRI concentrator array reflect refinement of that design. Three other 200–300-kW fields of Martin Marietta concentrator arrays are operating in Saudi Arabia and Australia and at Sandia in New Mexico.

Building on earlier work for EPRI by Bechtel Group, Inc., B&V has carried the conceptual design even a step further for a 100-MW central station photovoltaic plant comprising about 5600 18-kW arrays. Such a facility, including a control building and a 34.5/230-kV substation connected to a utility system, might spread over 618 acres (250 ha). It could be constructed in modular subfield increments of 10 MW (560 arrays), believed to be the optimum on the basis of scale economies and power conditioning (dc-to-ac inversion) requirements—one of the major components of balance-of-system costs.

BUT NOT ALL THE TECHNICAL ISSUES associated with the modules and arrays are neatly sewn up. Even the soldered connection between the cell package and the module housing requires further development to achieve the void-free bond needed for high reliability. On another front, B&V estimates the 18-kW array cost at from $23,000 to $27,000, but to satisfy a 6–8¢/kWh (current constant $) busbar energy cost in a mid-1990s installation, the array must cost no more than about $20,000. Some redesign may be necessary to hammer the installed array cost still lower.

Work continues, meanwhile, back at the module level, on developing manufacturing techniques for the Fresnel lens parquets. Researchers at Alliance Tool Corp.'s Fresnel Optics Division have identified a technique believed best for quickly and inexpensively doing this for single lenses, but applying it to entire parquets at a high production rate with minimal breakage or defects remains to be demonstrated.

Plans are being developed for testing complete modules and arrays as early as next year, which could involve EPRI in a cooperative effort with utilities and the DOE concentrator program at Sandia. The New Mexico laboratory has already independently measured the point-contact cell's performance, confirming the efficiency levels seen by Swanson at Stanford.

Looking ahead, in addition to evaluating array performance, key issues to be explored include verifying anticipated low operating and maintenance (O&M) costs. On the basis of the record to date from the few existing concentrator and tracking flat-plate systems, expectations are that O&M will account for less than 1¢/kWh of the target 6–8¢/kWh energy cost.

EPRI has the benefit of extensive performance data gathered since 1979 from a diverse assortment of now over a dozen utility-scale photovoltaic systems on which to gauge the substantially higher expected performance of the point-contact cell arrays. Two of the systems (one at Phoenix Sky Harbor and one at the Dallas–Fort Worth airport) are of the Fresnel lens concentrator type. Two others are the 1-MW and 6-MW Arco Solar, Inc., flat-plate tracking systems at Hesperia and on the Carrisa Plains in southern and central California, respectively.

In addition, since 1980 Pacific Gas and Electric Co. has been recording and analyzing data in a cooperative, cofunded program with EPRI on the long-term performance of over two dozen module types installed at its San Ramon, California, photovoltaic test facility. Major findings include confirmation of highly reliable operations and performance close to statistical predictions, although most modules do not reach peak power levels indicated by manufacturers' ratings. Recently, PG&E and Bechtel proposed building, with federal cofunding, an $80-million, 10-MW photovoltaic project to demonstrate advanced technologies not yet commercially available. The proposal calls for 3.5 MW worth of arrays to be installed in 1989, then another 6.5 MW in 1994. If those plans and funding materialize, EPRI's point-contact concentrator cell could be among the technologies included in the demonstration.

A winner in the wings

The final outline of full-scale demonstration and testing that evolves in the years ahead will depend to a great extent on utility cofunding with EPRI. Yet there seems a consensus in the photovoltaic research community that the point-contact cell and central stations designed around it show every indication of achieving commercial viability in time to satisfy some of the expected need for additional utility generating capacity in the 1990s.

"Swanson's success with the point-contact concentrator cell at Stanford has pointed the way to high efficiency in silicon solar cells," comments Robert Annan, director of DOE's photovoltaic division. "Up to then, the photovoltaic world seemed to have concluded that crystalline silicon just wouldn't make it economically in utility applications. But Swanson has forced everyone to revisit the technology, which with further development could lead to competitive bulk power generation. EPRI should be commended for its unwavering commitment to achieving high silicon efficiency."

DeMeo sums it up this way: "We're optimistic about the prospects for the point-contact cell for several reasons besides the demonstrated high efficiency. These include the very positive field experience we're seeing with existing systems of much lower efficiency. That's already a success story with today's technology from a system operation standpoint.

"What hasn't been shown is sufficiently high performance at affordable system costs. But we are encouraged by the prospects that there will be photovoltaic technologies with the needed combination of high performance and low cost, and the point-contact cell is one of them. It is also the one whose promise of high performance may be realized within the next five years." ■

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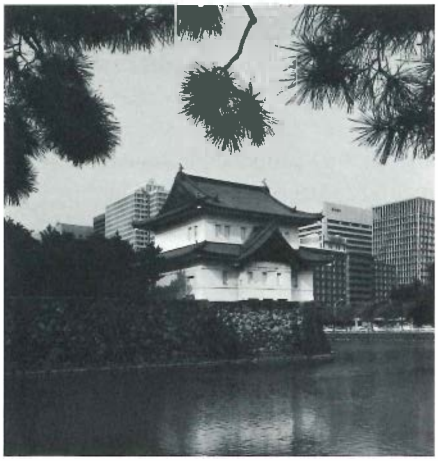
This article was written by Taylor Moore. Technical background information was provided by John Cummings, Edgar DeMeo, and Frank Goodman, Advanced Power Systems Division.

by Hiroshi Narita

ECONOMICS AND ENERGY IN 21ST-CENTURY JAPAN



Hiroshi Narita is president of the Central Research Institute of Electric Power Industry (CRIEPI), EPRI's counterpart for electric power R&D in Japan. This overview of Japan's socioeconomic and research expectations for the coming century was delivered at the 7th EPRI-CRIEPI General Meeting.

Long-term forecasting carries with it inescapable limitations and pitfalls, a fact reflected in the old adage, "Those who make predictions longer than 10 years in the future are not God-fearing." With so many variables exerting an influence for so long, the endeavor will inevitably result in some degree of inaccuracy. In addition, the forecaster's desires and aspirations can heavily color the outcome, no matter how objective he tries to be.

Despite these factors, long-term forecasts can be a valuable—even essential—tool in maintaining vitality and providing strategic direction. For a research organization, the approach is not to try to make accurate predictions of individual events but to forge a long-term vision of probable future conditions, identifying those requiring R&D responses and conducting the research that will provide the best preparation for meeting the future's demands.

This is the rationale behind a forecast of socioeconomic trends conducted each year by Japan's Central Research Institute of Electric Power Industry (CRIEPI). The most recent forecast sought to paint a picture, in both structural and qualitative terms, of social and economic conditions in Japan for the early twenty-first century—to about 2010. Initial input for the forecast consisted of impressions gathered by questionnaire from 430 individuals of various backgrounds.

Although response to this latest questionnaire was characterized by a wider scattering of opinions than in previous years, there was enough consensus to generate a number of general conclusions. According to the survey, the international free-trade system will enjoy relatively stable growth. Social values in Japan will continue to shift from concern over material goods to increased interest in self-fulfillment and individual needs—the trend toward developing a mature society will continue. The application of advanced technologies is expected to lead to improvements in labor productivity and the living environment. On the energy side, diversification of supply sources for electric power, including the growth of distributed generation, is seen to be a continuing trend.

The survey impressions create a rather optimistic scenario. Using this view as a starting point, CRIEPI has applied its own quantitative analytic models to flesh out a more detailed picture of twenty-first-century Japan, its economy, societal changes, and energy needs. The results provide a fresh look at Japan's incentives in the energy arena and give sharp definition to CRIEPI's research strategy for the coming quarter century.

The path to a mature economy

Future prospects for the world economy do not support an overly optimistic outlook, and difficult problems are developing from all directions. The United States is worried about budget and trade deficits, Europe is searching for solutions to long-term structural economic problems, the newly industrialized nations are worrying about future growth, and the developing countries are faced with the burden of debt. Under these conditions, Japan is being asked to reduce its balance of payments surplus while achieving an inflation-free continuous expansion; such actions are expected by world governments to contribute to a revitalization and stabilization of the world economy.

With regard to the trade imbalance problem, the increase in value of the yen should have a retarding effect on exports, and the import of manufactured goods is being encouraged as a fundamental policy instead of the former concentration on importing raw materials. Preliminary calculations indicate that—given this policy shift and the anticipated tightening of the oil supply situation in the second half of the 1990s—Japan's oil import costs will probably increase, with the possibility that its balance of payments will move into the red during the first decade of the twenty-first century.

The key to the second goal—inflation-free growth—is a good balance between overall demand and supply (potential GNP), rise in the value of the yen, and continued improvement in productivity. We are projecting an annual economic growth rate of 4% up to the year 2000 and a 3% growth rate for the following 10 years. Given a per capita GNP exceeding $10,000, the projection is definitely not low. It is anticipated that relative price stability will continue, with an average inflation rate of 2 to 3% expected for the next 25 years. Even with the increase in petroleum prices expected about 2000, growth in value of the yen and steady improvements in productivity will provide a restraining force on inflation.

In this connection, preliminary calculations by using our oil market model indicate that the current oil glut will end sooner than expected, and it is highly probable that the oil supply and demand situation will become tight again during the 1990s. The use of petroleum by the 70% of the earth's population living in the developing countries, for example, will surely increase. The effect of oil prices on future exploration and production from proven reserves remains unclear. However, there is an ultimate limit to future production, and if worldwide dependence on petroleum continues, sudden future increases in petroleum prices would not be surprising.

The road that Japan will walk as it becomes a mature advanced nation will not be smooth. The effect of the rising value of the yen on the import-export situation will necessitate changes. Also, the burden of social welfare costs will increase with the aging of the Japanese population. However, personal income and expenditure will increase alongside rising corporate capital investment, and the steady movement toward maturity will focus increased emphasis on growth of the domestically oriented aspects of the economy.

As with the mature economies of the developed nations, Japan must meet diversified consumer needs and promote technologic innovation in order to grow. The diversification of needs is being driven by consumers expressing their individuality and having the time and resource to modify their lifestyles. As an old proverb states, "Courtesy is possible when the necessities of life are met." In modern Japan, the three basic necessities of clothing, food, and shelter are more or less satisfied, although as often mentioned, qualitative deficiencies in housing still exist.

In addition to addressing unsatisfied demand for housing improvements, expenditures are expected to increase rapidly for individual access to educational, cultural, and recreational facilities. With the growing trend toward a five-day workweek and longer vacations, suppliers of merchandise and services will have to supply increasingly smaller niche markets to meet the diversifying desires of consumers.

The knowledge-intensive industrial structure

Changes in traditional industry and the rise to prominence of new industries are tied to the advance of technology; microelectronics, of course, will be fundamental to these changes. New materials are also expected to represent major new business opportunities that will be comparable to the impact of steel, nonferrous metals, and petrochemicals on the Japanese economy in the postwar era.

Along with expansions in individual sectors, industry as a whole will become more knowledge-intensive. The trend to knowledge intensiveness is connected to the growing role of information in society. Preliminary calculations indicate that information-related business in its broadest meaning (including the computer industry, communications, and mass media) will expand its share of Japan's GNP from 18% in 1983 to 30% in 2000. Also, information-related employment will expand from 1 in 2.4 in 1983 to 1 in 2 by 2000.

Although technologic innovation creates valuable new business opportunities, a number of socioeconomic problems are also created. For example, with expansion of the service sectors of the economy and the tendency for production to be separated from design, there is a possibility that so-called hollow corporations may appear in Japan. Because of Japan's lack of natural resources, it is unlikely that the ratio of services to manufacturing will become as high as that in the United States. However, this question requires careful analysis from the point of view of industrial technology.

Also, although the dependence on information is unlike dependence on oil, if primary information sources were concentrated in a few major countries, there might be a fear that Japan would become an importer of various sources of information. In that future scenario, if for some reason the supply of information were stopped, there is the possibility that the effect could be greater than the oil shock. In any case we need to grasp the trends toward expansion of the service and information sectors of the economy and to inherent problems and possible frictions.

Energy and electricity supply and demand

The social and economic changes described above will inevitably affect the energy and electricity supply and demand situation. CRIEPI's analysis anticipates a 2% average growth rate for energy consumption through 2000, with little if any growth thereafter. A leveling off or even decline in the energy-intensive basic materials industry (expected at the start of the twenty-first century) makes energy growth in the industrial sector particularly unlikely. Detailed calculations show that GNP energy consumption elasticity will be 0.6 through 2000 and will drop to about 0.3 after 2000.

Growth in demand for electricity will be higher than that for energy overall—about 3% per annum through 2000 and 2% per annum after 2000. Of course this takes into account anticipated changes in economic structure that will continue after the turn of the century, including lower overall industrial electricity consumption but firm demand in the residential and commercial sectors. Electricity demand in these latter two sectors will be boosted particularly by the new ventures of the third industrial revolution and the qualitative diversification in the service sectors of the economy. As a result, electricity's share of total energy is expected to expand from the current 38% to 43% in 2000, to 50% in 2010, and to 62% in 2030. With information and electronics technology as a core, it is predicted that a new electricity-based society will be realized.

Japan's energy supply policy will continue to be based on the lack of domestic energy sources and the need to balance economic and security considerations. Thus, nuclear power will continue to be the center of efforts to diversify generation sources, while efforts to conserve energy and reduce dependence on oil will continue. The share of nuclear energy in primary energy supply will expand from the current share of approximately 7% to about 16% in 2000 and to about 35% in 2030. Development of hydroelectric, geothermal, and other domestic sources of energy will also be pursued within their limits. New oil-fired units will not be constructed.

In 1985 the output of nuclear power units in kWh was approximately 25% of total electricity output. Preliminary estimates indicate that nuclear's share will grow to about 40% by 2000 and continue to increase after that time. Pulverized-coal-fired plants accounted for less than 9% of electricity output in 1985. After 2000, gasification–combined cycle, molten carbonate fuel cell, and other advanced-generation systems will be commercialized and available to supplement conventional coal technology. The share of all coal-based generation systems in 2000 will be about 17%, with future growth anticipated. Hydroelectric power, which is Japan's only major domestic energy source, will maintain about a 20% share.

Oil-fired generation is currently the largest component of Japan's electric power generation, with a 31% share of the power generated in 1985. Because new units will not be built, the share of oil-fired generation will gradually decline to about 13% in 2000; this type of generation will be used only for peaking after 2000, so its share will continue to decline.

Solar photovoltaic generation, wind-powered generation, and ocean energy technology development are being supported primarily by the Japanese government. These technologies are expected to have little impact on power generation in 2000, and it is difficult to predict the future roles of these technologies.

CRIEPI's long-term research

To bring the new electricity-based society to full realization, the electric power industry must meet the following three basic challenges. First, electricity supply costs must be reduced. Rates for electric power are relatively high at the present time, and reduction and rate stabilization over the long term are necessary for the national economy of the future. Second, the quality of energy supply must be improved to ensure satisfaction of demand. Given Japan's limited domestic energy supplies, it is necessary to create an electricity supply system that is not greatly affected by fluctuations in oil prices, exchange rates, and other external factors. Third, we must obtain the understanding and confidence of society. The importance of such support has been clearly shown to electric power companies in their efforts to site generation and transmission facilities.

CRIEPI is selecting areas for research with the aim of aiding the electric power industry in meeting these three objectives under the conditions that have been forecast for the twenty-first century. For reducing costs and achieving energy-independence, work in nuclear power holds the most promise. CRIEPI is concentrating strongly on four areas of nuclear research to ensure that this promise is fulfilled: the nuclear fuel cycle, the fast-breeder reactor (FBR), power plant siting, and the development of modular nuclear reactors.

The nuclear fuel cycle is a primary consideration in terms of public confidence in nuclear power, and Japan is already in the process of dealing with this important concern. Construction of facilities for uranium enrichment, light water reactor (LWR) spent-fuel storage, power plant waste storage, and storage of wastes returned from overseas reprocessing is planned to begin in 1987. Research to support the implementation of such back-end measures is a high-priority area in CRIEPI's research program.

The pursuit of energy self-reliance for Japan is one of the major motives for development of the FBR. However, to be commercialized, FBRs must become economically competitive with conventional LWRs. CRIEPI's R&D effort in this area is centered on developing technology that will help reduce costs and increase confidence in FBRs. Aseismic design, secondary-tank approaches, and other new design concepts are being considered for priority in CRIEPI's FBR research effort.

Research on plant siting is also important for Japan's nuclear future. Conventional sites with geologic characteristics suitable for nuclear plants are becoming scarce. Thus, technology for siting on Quaternary foundations, underground, on floating platforms, and in other unconventional sites has to be developed.

For cost reduction, modular nuclear reactors would offer economic benefits from such factors as learning-curve advances from production of multiple units, economies in design, and shortening of construction time. Also, given the anticipated reduction in the growth of demand for electricity, smaller modular units might provide a better supply-demand match than the large units presently being constructed. CRIEPI is evaluating the feasibility of modular-type nuclear plants, and initiation of R&D on modular plants is being considered if the results of current studies are positive.

Although continued expansion of nuclear power is key to Japan's energy future, coal-fired power generation technologies, such as gasification–combined cycle and molten carbonate fuel cells, will provide an important supplement of low-cost, clean generation in the twenty-first century. Research on these technologies was initiated in 1982 by our Institute. A 2-t/d fundamental test facility is currently being operated as part of our effort on gasification–combined-cycle power generation; simultaneous development of a 1-kW fuel cell will not only advance another fundamental new technology but also allow assessment of the feasibility of combining both technologies into an integrated system. The objective of the research is to commercialize both technologies by 2000.

As with modular reactors, coastal waters are being considered for siting gasification–combined-cycle generation units and molten carbonate fuel cells. Other technologies, such as phosphoric acid fuel cells and new types of battery energy storage, could be sited inside metropolitan areas in dispersed configurations. CRIEPI is actively pursuing the development of such generation and related technologies as part of the overall systems technology development approach.

Electricity and the information-oriented society

The expanding role of data and information processing in modern society is providing both problems and opportunities for electric power companies. When voltage drops of less than a tenth of a second can cause computer outages, questions of power quality and transmission reliability take on added importance. CRIEPI research on high-reliability automation is addressing these problems directly. R&D on management information systems using knowledge engineering techniques and the development of technologies for two-way communication with the demand side are increasing the efficiency and economy with which power companies serve their customers. CRIEPI is also doing fundamental research to support development of wide-area communication nets, and electric power companies themselves may eventually enter the information and communication industry.

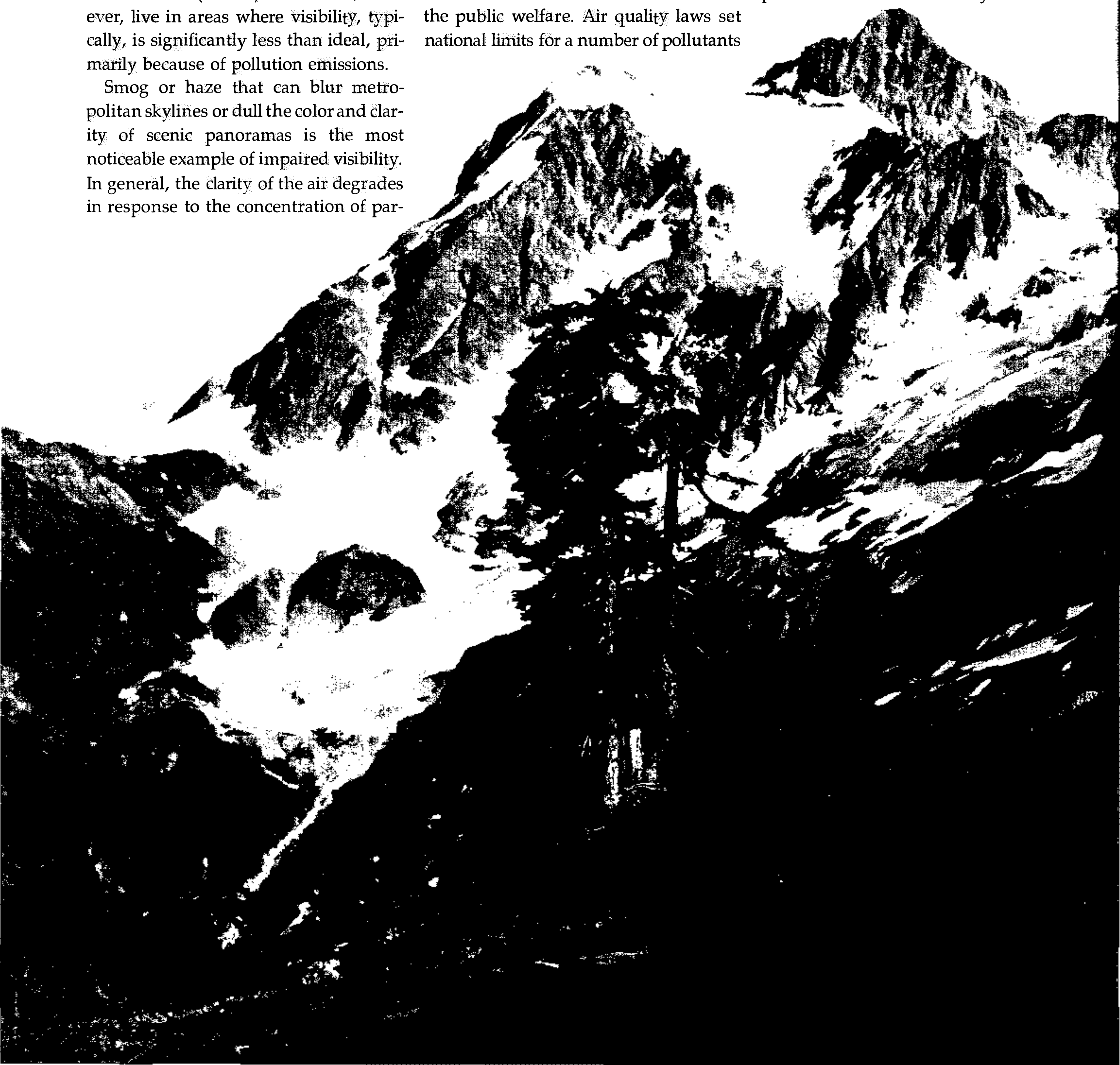
As we look ahead to the early twenty-first century and forecast socioeconomic and technical trends, it is clear that our role is expanding. Electricity is simply becoming more important to the way the world will work in the coming century. In addition to meeting the power needs of our customers, the electric power industry should also help promote the general welfare of society—I believe that we all share this feeling. And in sharing their research, EPRI and CRIEPI will meet the challenge of energy and its effective use in the upcoming era. ■

On a clear day you can see forever, the song goes. Actually, even under the best conditions, when the atmosphere is absolutely free of moisture and pollutants, light-scattering by molecules of the air itself limits the maximum visual range to about 390 km (240 mi). Most of us, however, live in areas where visibility, typically, is significantly less than ideal, primarily because of pollution emissions.

Smog or haze that can blur metropolitan skylines or dull the color and clarity of scenic panoramas is the most noticeable example of impaired visibility. In general, the clarity of the air degrades in response to the concentration of particles in the air from both pollution and natural sources, with weather and atmospheric moisture as complicating factors. It may be a visible plume from a specific local emissions source or a much larger regional haze caused by emissions from many sources, often distributed hundreds of miles downwind.

Whatever the origin, such episodes are a problem—visibility is an esthetic resource, part of what the landmark environmental laws of the 1970s defined as the public welfare. Air quality laws set national limits for a number of pollutants known to contribute to visibility impairment, and visibility is one of several air quality values that federal and state environmental agencies consider in regulating emissions and air quality.

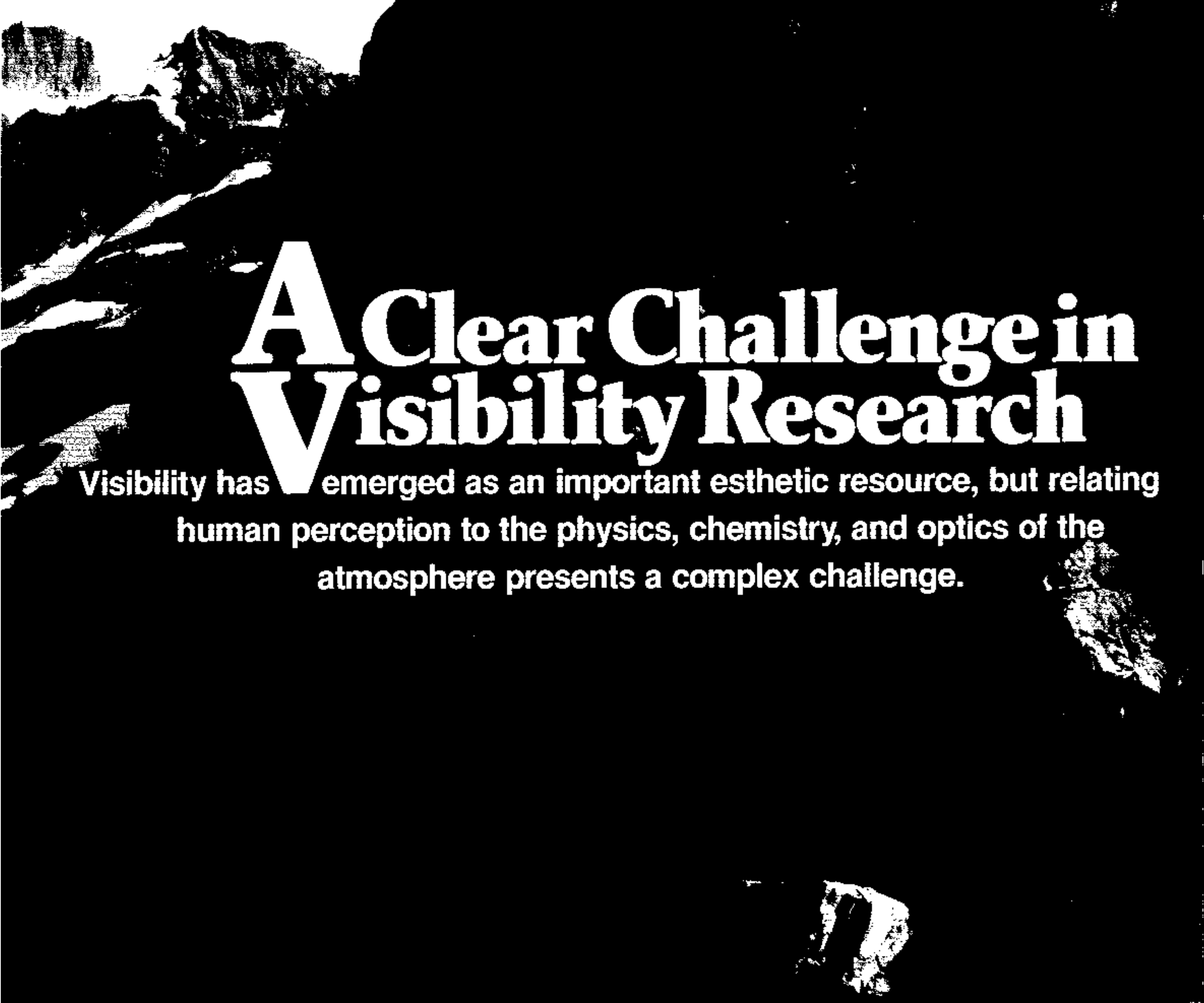
Moreover, visibility is singled out in the law for protection around most of the national parks, monuments, and wilderness areas. Even in parts of the country where existing air quality is generally good, such as in the intermountain West, potential effects on visibility often con-



strain the siting and permits of new fossil-fuel-fired power plants and other sources of industrial emissions.

While noting that continued research is needed on real and perceived trends in visibility in the United States, in 1981 a National Research Council panel concluded that scientific investigation over the past 50 years "has resulted in a good basic technical understanding of atmospheric visibility and its relationship to ambient air quality—much better, in fact, than the understanding of health effects, damage to materials, acid precipitation, or ecologic effects."

Yet visibility remains unique among air quality issues for several reasons. One is



A Clear Challenge in Visibility Research

Visibility has emerged as an important esthetic resource, but relating human perception to the physics, chemistry, and optics of the atmosphere presents a complex challenge.

that it inherently involves human judgment, perception, and subjectivity. No camera or scientific instrument measures visibility as humans perceive it, yet air quality regulations to protect visibility are tied directly to human perception. There is a continuing need for basic science, but the research must also focus on relating the physics and chemistry of the atmosphere to the less easily measured aspects of human perception.

A mixed trend

As with other air quality issues, the complexity of materials, sources, and processes involved in visibility resists most attempts to generalize about long-term trends. Still, some broad historical characterizations have been made. One of the most lucid was contained in a recent National Academy of Sciences (NAS) report. Using airport observation data from 35 eastern rural sites, as well as other data records, John Trijonis found that visibility, in general, improved from the early 1940s to the early 1950s; then after a brief level period, it declined from the late 1950s to about 1970, finally fluctuating without any apparent trend between 1970 and the early 1980s. He found the overall decline in recorded visual ranges in the last three or four decades statistically significant. The data also show that rural concentrations of atmospheric sulfate, a pollutant implicated in visibility degradation, increased from the 1960s to the 1970s, although the percentage of change was greater than that for visibility itself.

Summarizing other researchers' analyses of data from the 35 eastern sites by region, Trijonis observed that the Northeast did not share in the overall visibility decline from the 1950s to the 1970s but apparently experienced a slight improvement; the Midwest underwent a moderate decline in visibility, with similar but less certain indications for the North Central states; the Southeast demonstrated an especially pronounced deterioration in general visibility during the 1960s.

Historical data for the East on visual range also show an apparent trend of declining summertime visibility over the last 30 or 40 years that coincides with increased sulfate concentrations. "In fact, this particular seasonal trend is one of the most salient features of air quality history and has been pointed out by most workers who have studied trends in visibility, turbidity, or sulfates in eastern North America," Trijonis notes in the NAS report. "The summer was a season of relatively good visibility during the 1950s but became the season of distinctly lowest visibility and highest sulfate by the early 1970s."

Several studies attribute this deterioration of visual air quality in the summer to increased emissions of sulfur oxides (precursors to sulfates) from coal-fired power plants as a result of increasing electricity demand. Other researchers, noting the important role that atmospheric water can play in visibility reduction, point out that average summer humidity and stagnant weather episodes also increased in the East during that time.

Regional haze and visible plumes from identifiable sources typify eastern visibility problems. In the West, where median visual range is 150 km (95 mi) or more versus 15–25 km (10–15 mi) in the East, the regulatory focus is more on the prevention of any significant deterioration of visibility in mandatory Class I areas, including the national parks and wilderness areas.

Moreover, the chemical composition of haze in the West is typically different than in the East. Haze results from an aerosol of fine particles and gases suspended in the air. Although in parts of the Southwest sulfates dominate haze aerosols, the most abundant constituent in the West is generally organic material, followed by sulfates, the reverse of their order of importance in eastern haze. Los Angeles smog is a special case in that it is dominated by nitrates, which result from the conversion of nitrogen oxides emitted by automobiles, power plants, and other industrial activities.

In addition to lower average aerosol concentrations, the drier atmosphere in the West is a key factor in the dramatic difference in visual range. At a relative humidity of about 70–75%, common in the East, water collects on some solid particles, including sulfates, causing them to change to liquid droplets and to grow to a size that increases their ability to scatter light severalfold.

Keeping account of light

Light-scattering and, to a lesser degree, light-absorption are the optical mechanisms involved in visibility impairment. Specifically, visibility is reduced when some of the light reflected from a target, such as a landscape feature, is scattered or absorbed by particles and gases in the air before it reaches an observer. Fine particles in the 0.1–1-μm range are the most efficient at scattering light because their size is comparable to the wavelength of visible light. They also tend to accumulate and remain for many days in the atmosphere, often carried great distances by the wind before they are removed by precipitation or contact with surfaces on the ground.

The only gas of appreciable quantity in the atmosphere that absorbs light is nitrogen dioxide (NO_2), which can give smog or visible plumes near emission sources a yellowish hue because blue light is preferentially absorbed and more red light gets through. But except for urban smog and smokestack plumes, NO_2 generally accounts for only a few percent of visibility degradation.

Scattering and absorption of light by particles are the principal factors in reduced visibility. Carbonaceous materials (elemental soot from combustion or organic carbon) both absorb and scatter light, with a greater effect per unit weight than particles that only scatter light. Carbon's role in visibility has been recognized relatively recently; such particles are believed to dominate haze in the West and are second only to sulfates in the East.

In addition to carbon, the main constituents of aerosol particles are sulfates from sulfur oxides, nitrates from nitrogen oxides, water, and wind-blown dust. They interfere with light according to their size, shape, and chemical composition.

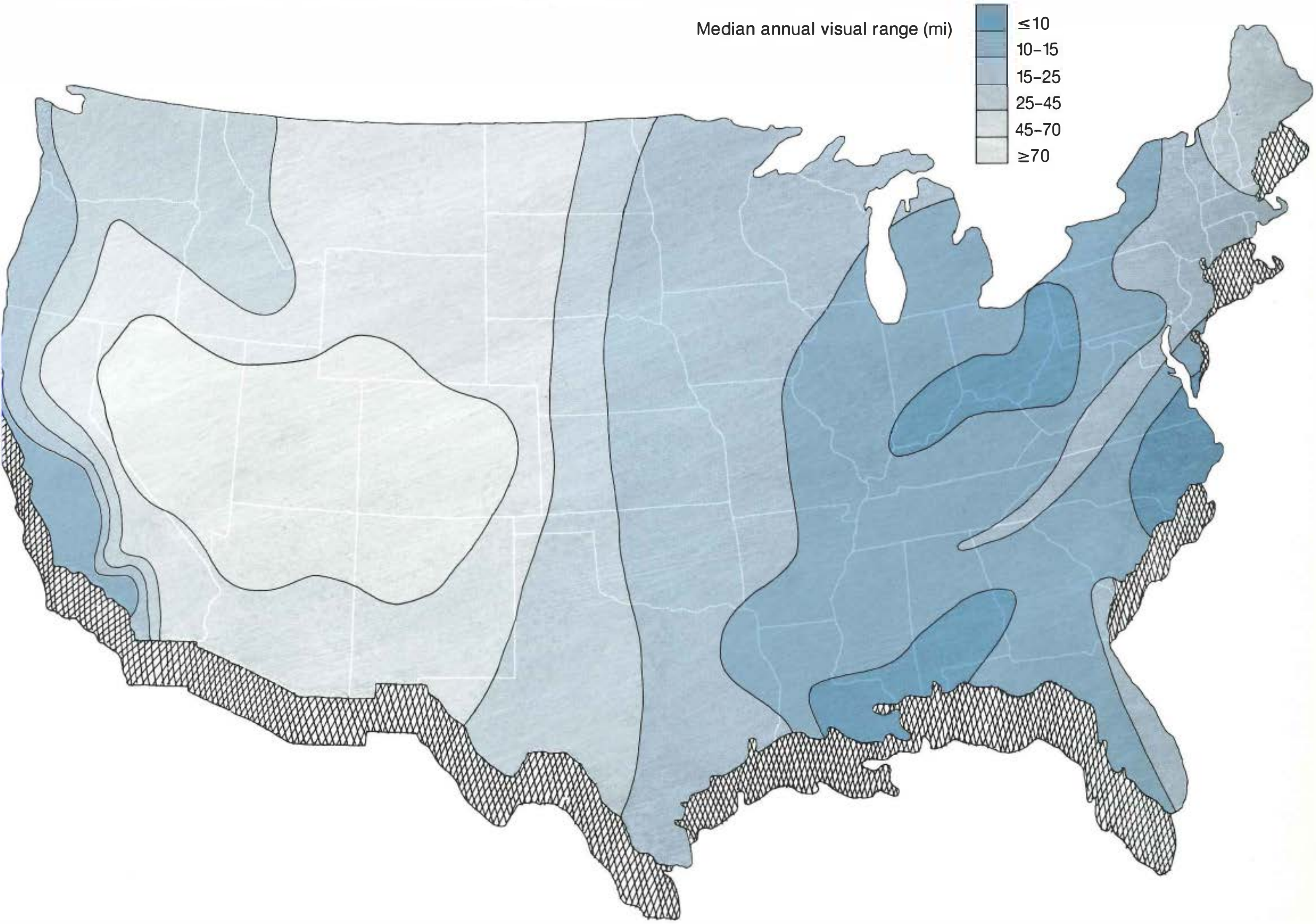
Sources of these materials are both natural and man-made. They include, but are not limited to, direct emissions from combustion sources and many other industrial processes, gaseous pollutant emissions that form secondary particles, and soil disturbance from agricultural plowing and unpaved-road traffic.

According to the Environmental Protection Agency (EPA), the combined effect of particles on visibility impairment from natural sources is believed to be insignificant compared with man's activities, with a few exceptions. Forest fires in the West are a frequent source of carbon-dominated regional haze. The dust plume injected into the atmosphere by the eruption of Mount St. Helens in 1980 produced a classic case of multistate regional haze.

Once in the air, the fate of particles of concern in visibility depends heavily upon weather conditions and atmospheric processes that change them physically and chemically and sometimes carry them great distances. These processes—the link between sources of emissions and the visual quality of air downwind—are the subject of intensive research on a broad front because of their implication in both acid rain and visibility.

The View Across the Nation

Visual range varies greatly across the United States, with maximum values generally in the drier atmosphere of the intermountain West and poorer visibility typical in the eastern part of the country. Isopleths on the map indicate median annual visual range characteristic of broad regions in the country. Seasonal variations can be significant (summertime visibility is usually reduced because of higher humidity or stagnant weather), although the general outlines of the isopleths do not change substantially.



To understand the influence of a change in emissions on visibility in a given region, field studies must establish the nature and quantities of emissions, regional air quality climatology, the variability of visual range, the concentrations of aerosols, and meteorologic variables both for baseline descriptions of existing conditions and to identify long-term trends. Such detail is also necessary to resolve the large-scale spatial patterns in annual and seasonal visibility values. Determining climatic influences, such as the higher relative humidity in the East, is essential in comparing visibility across regions. Relative humidity may not always be the most important meteorologic factor; the temperature distribution over an area is also important and is related in part to local terrain. And, of course, the wind can stir up a lot of visible dust, particularly in the West.

Visibility research

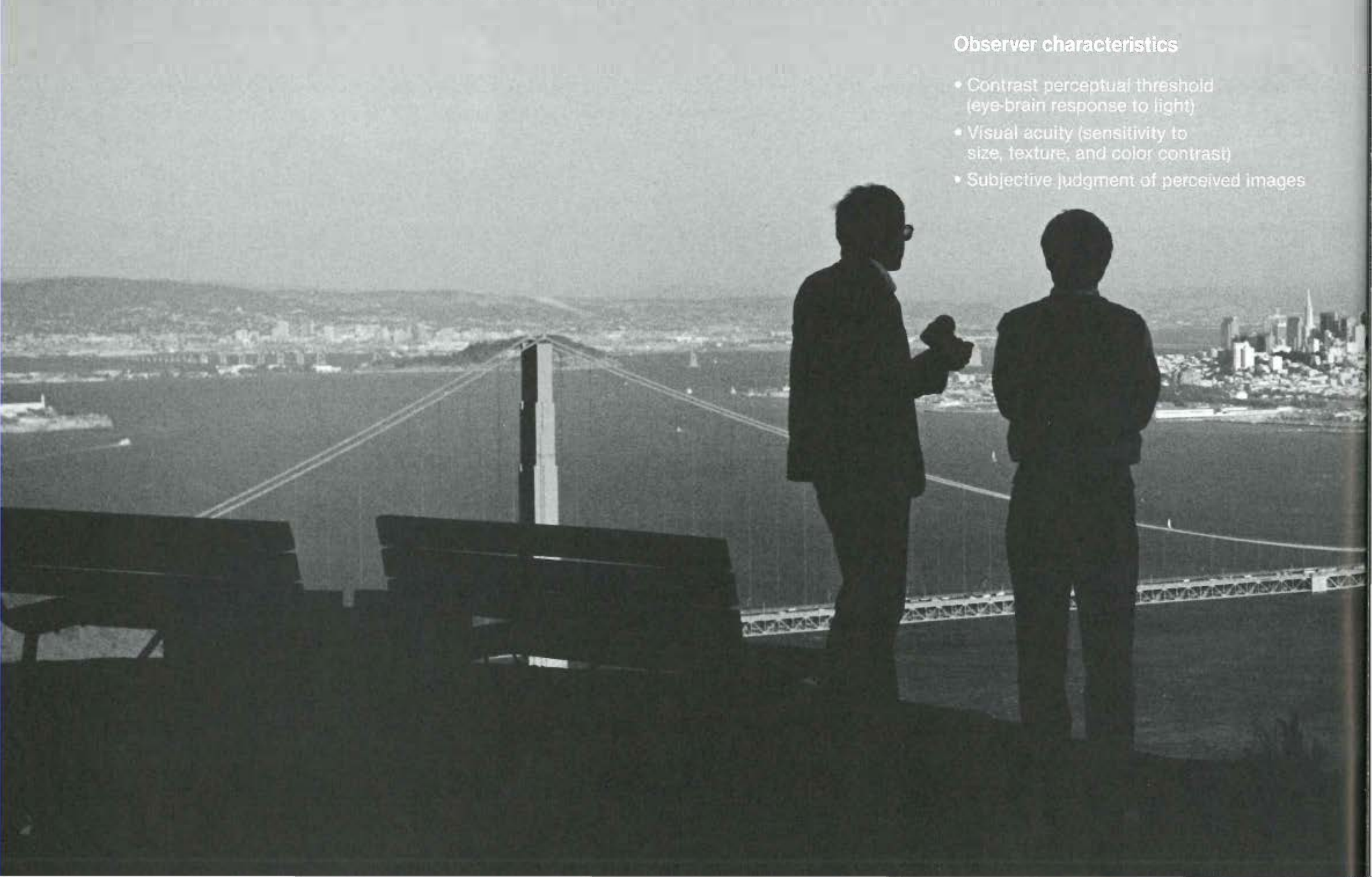
Protection of visibility was mandated by the 1970 Clean Air Act Amendments. This general recognition by Congress of the importance of visibility to the public welfare was elaborated by further amendments in 1977, which established as a national goal "the prevention of any future, and the remedying of any existing, impairment of visibility in mandatory Class I federal areas" resulting from man-made air pollution.

By the 1970s visibility issues were attracting attention from the aviation industry and the military because of the implications for air traffic safety and weapons testing. The Clean Air Act and its amendments quickly elevated visibility as an important topic for research by other federal agencies, including EPA, which has regulatory responsibility for enforcing the law, and the National Park Service, which began long-term monitoring of visibility trends in parks and wilderness areas. Industries that produce emissions leading to particle formation in the atmosphere, including the electric power industry, also began sponsoring visibility research.

Since 1977 EPA, the National Park Service, and the Department of Defense

Vision in the Atmosphere

The visual quality of a scene viewed by an observer is the product of several factors in addition to atmospheric conditions. Even when the atmosphere is very transparent, the characteristics of the source of illumination, the viewed target, and even the observer influence a viewer's perception of the scene. Instruments for measuring visual air quality are still too limited in their ability to integrate or differentiate these factors, but an important element of EPRI's visibility research is aimed at identifying their relative roles.



have conducted or collaborated on a number of visibility studies. Individual utilities, particularly Southern California Edison Co. (SCE) and the Salt River Project (SRP) in Arizona, have also sponsored visibility research, including development of improved instruments for atmospheric optical measurements.

These studies variously sampled and characterized emissions and atmospheric aerosols, investigated or developed techniques for aerosol sampling or optical measurement, established correlations between optical indexes and human observation, or examined long-range aerosol transport by attempting to relate visibility to results of trajectory model calculations. The ultimate goal of visibility research is to develop a basis for relating emissions to aerosols, aerosols to light extinction, and light extinction to human perception. Utilities are particularly interested in determining the contribution their emissions make to visibility impairment.

EPRI became involved in visibility work in 1980 as part of its regional air quality studies (RAQS). In the West, RAQS began as a 5-site network that later grew to 11 monitoring stations, which took almost daily optical and aerosol measurements of known precision for nearly two years.

One particularly significant finding was that roughly 40% of the sampled fine-particulate matter at the monitoring locations was not sulfate but carbon. The project provided baseline visibility data for 11 western sites, but these were so widely dispersed that each could be representative of a subregion from a meteorologic perspective. "The monitoring stations were not deployed to study the origin and evolution of hazes in terms of time and space," notes Peter Mueller, subprogram manager for EPRI's air quality studies in the Environment Division. "To do so requires a subregional network. Collectively," Mueller continues, "all the studies provide a great deal of information on visibility and aerosols in the West, but they also show the need for further research to fill gaps in our knowledge.

"Questions remain for several reasons. Dissimilar sampling and analytic methods make it difficult to compare results among studies and accumulate a consistent data base. Some studies have been of such short duration that seasonal and yearly trends are not sufficiently defined to sort out the relative importance of weather and man-made emissions. In addition, the number, type, and frequency of measurements have often not been adequate for apportioning changes in visibility to specific sources," says Mueller. Moreover, models to relate these physical measurements to human perception of visibility are still under development.

A sharper focus

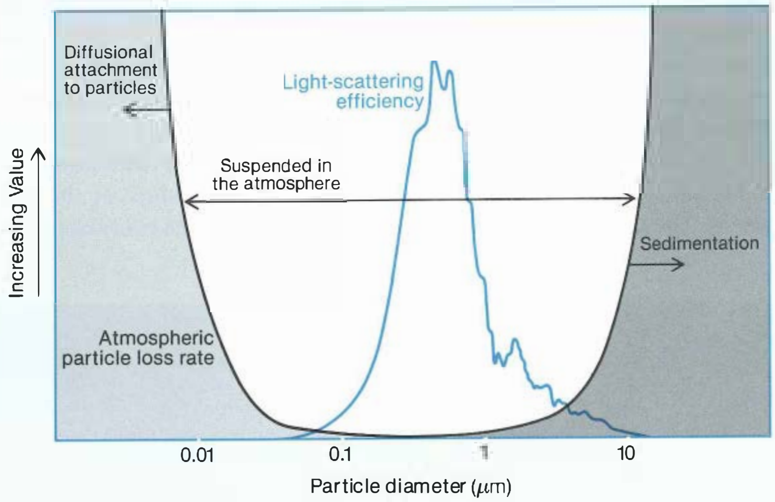
Despite their shortcomings, earlier studies have guided the design and implementation of a major five-year effort now under way that is called the subregional cooperative electric utility, Department of Defense, National Park Service, and Environmental Protection Agency study, or SCENES. In addition to the federal agencies, SCENES participants include EPRI, SCE, and SRP. The project is intended both to produce a method for assessing visibility on a subregional scale and to develop the knowledge necessary to characterize and maintain visual air quality in the Southwest.

Operating since early 1984, SCENES includes 12 monitoring sites, with additional sites that have been part of previous, continuing, or short-term separate projects in the southern parts of California, Nevada, and Utah, along with northern and central Arizona. Mueller, who serves as chairman of the interagency working group of SCENES sponsors, says, "The study area offers a desirable real-world experimental situation because most of the sources of man-made emissions are at large distances along the air mass trajectories that influence flows in and out of the Grand Canyon region."

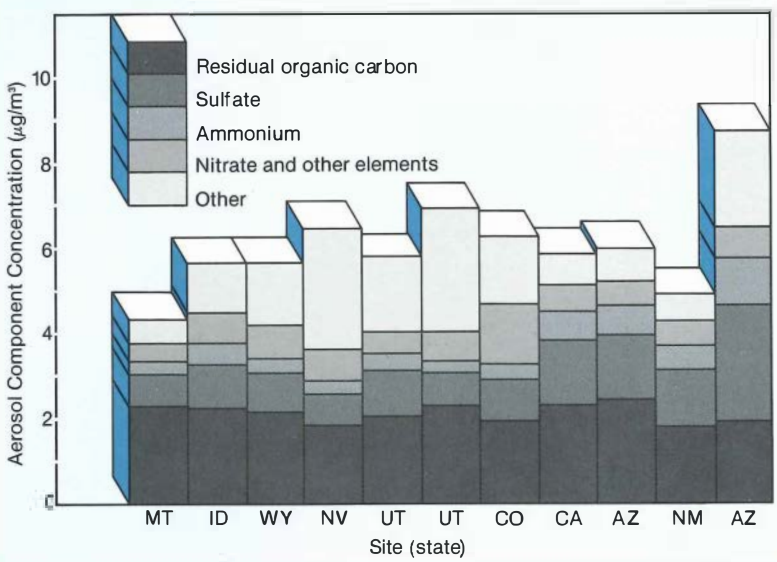
The SCENES region encompasses the

Fine Particles: Now You See Them . . .

Light-scattering and absorption by particles are the principal mechanisms influencing visual air quality, although lighting conditions play an important role. Fine particles in the size range of 0.1–1 μm in diameter are the most efficient in scattering light because their size is comparable to the wavelength of visible light. Fine particles—the result of industrial, urban, or natural emissions—also tend to remain suspended longest in the atmosphere. Smaller particles tend to attach to larger particles, and particles larger than about 1 μm in diameter tend to quickly settle out of the atmosphere.



The major chemical components of fine particles vary, depending on location and circumstances, but organic carbon, sulfate, ammonium, nitrate, and fine-soil dust are the main constituents. Data from 11 monitoring stations in EPRI's 9-state western regional air quality studies project found that residual carbon, a portion of which may be from natural sources, is a more important component of haze in western locations than previously thought.



The Human Element: In the Eye of the Beholder

Computer models can tell us a lot about the relationships between emissions, atmospheric processes, and downstream air quality, especially the more detailed and realistic they are made by field studies. Yet it is the human element that is most difficult to account for in visibility research.

Instruments are available for measuring different aspects of atmospheric optics. But the actual experience of taking in a view of the outdoors involves more than instruments can now measure. Human judgment of visual air quality is both a matter of sensory perception by the eye-brain system, for which the psychophysiology is fairly well developed, and cognition, including subjective esthetic value judgments that "are beyond the scientific pale," according to Peter Mueller of EPRI.

Even relating the physiology of vision to instrumental optical measurements is difficult because color—a key element, along with visual range and contrast, in the regulatory definition of visibility—is defined by what humans can perceive. "Instruments can only measure the wavelength distribution of light, which varies greatly, depending on circumstances," notes Mary Ann Allan, research analyst in EPRI's Environment Division. "Instruments can never replace the human observer, but they are essential for routine observation. So we need a way to correlate human observations and instrument measurements. One approach is based on color standards that were developed for matching paints and cloth. EPRI is doing research to apply this to landscapes.

"In addition to color, the contrast threshold is central to human perception. In recent years contrast has become a widely measured visibility index. Yet even this factor is influenced by ambient lighting conditions, the observer's experience, visual acuity, and the content of the scene," Allan notes.

Adds Mueller, "Results from EPRI's 11-station network for the western regional air quality studies tell us that simple contrast measurements are insufficiently precise to relate aerosols to visibility, but the measurements that have been made are useful for characterizing average annual and seasonal visual ranges. As a result of these findings, some novel concepts are now being field-tested under sponsorship of EPRI and the National Park Service."

EPRI funds research at the University of Utah Research Institute and the University of Southern California (USC) in what are known as the psychophysical aspects of visibility. Researchers at Utah are striving for a calculatory procedure to relate visual measurements to the actual appearance of a scene and attempting to verify the approach in field studies at the Grand Canyon. USC investigators, meanwhile, are working on a device for taking measurements that relate directly to human visual perception.

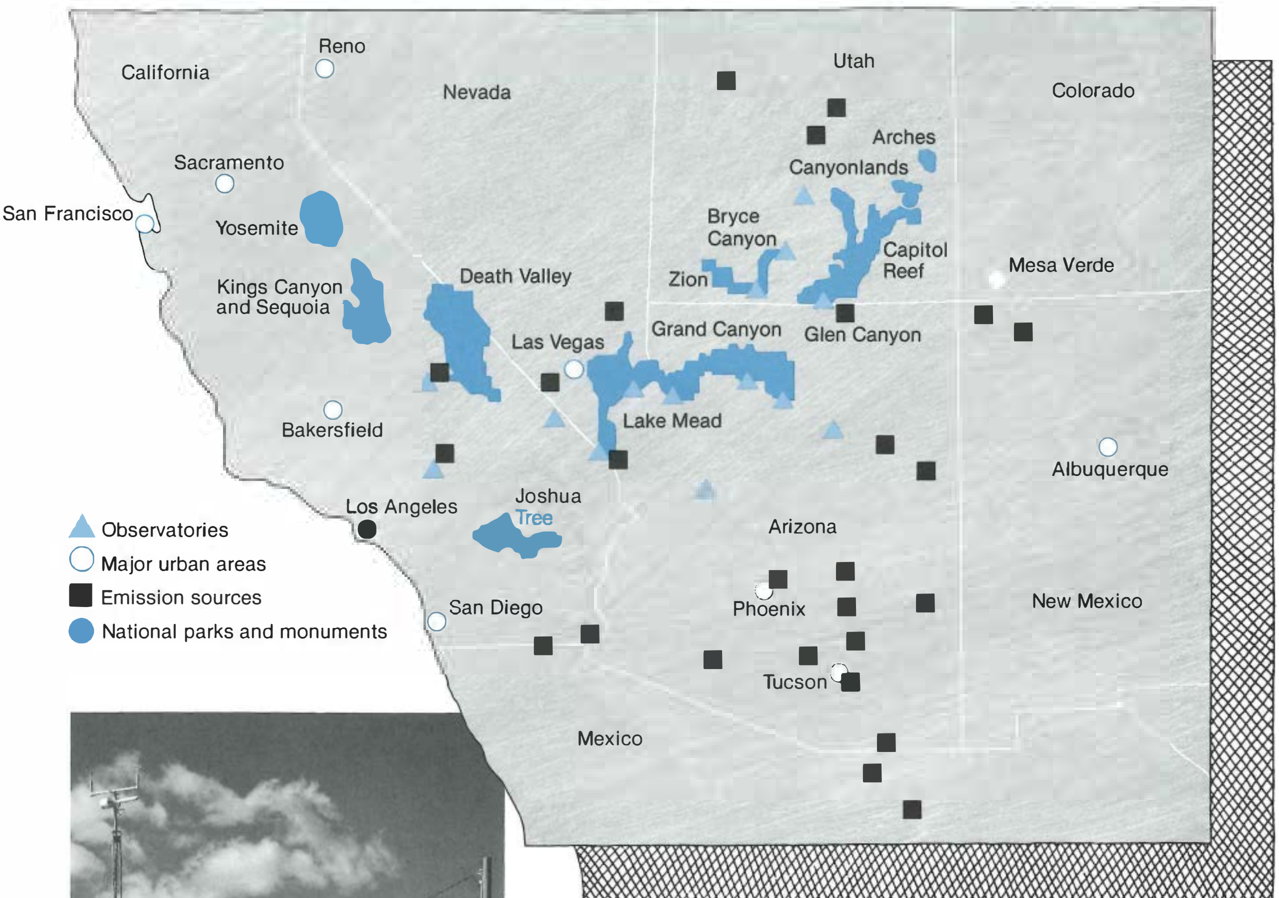
Called a visual colorimeter, the USC instrument is expected to be used to test and refine the visibility modeling work at Utah; researchers there have already applied a prototype of the instrument in field studies. Explains Mueller, "With the colorimeter, the observer looks at a scene and dials into the instrument what he sees in quality, color, and brightness until what he sees through the instrument matches the naked view. The instrument then provides an index that can be related to the optics of the atmosphere as perceived." A field-proven model of the colorimeter may be available in 1988.

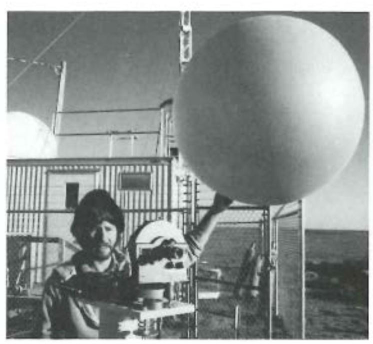
Apart from perception, the value judgments of humans are also important in regulation and research on visibility. What is good visibility worth to an individual and to society at large? What are people willing to pay for good visibility? How does this value compare with the cost of achieving good visibility? In addressing its mandate under the Clean Air Act, EPA has tried to place a dollar value on visibility in terms of public welfare. Using human survey methods that primarily amount to showing people photographs of scenes with different visibility qualities and asking how individuals rank one photograph over another, the agency estimates a high value to the public of improving visibility in the eastern United States; such values are input to cost-benefit calculations, as well as analyses of possible regulatory standards for emissions.

But this bidding game (contingency evaluation) approach can introduce bias and present procedural difficulties that render the results unreliable. EPRI's Environmental Risk Analysis Program is sponsoring research by psychologists at the Eugene Research Institute in Oregon and by economists and others at Resources for the Future, Inc., and the University of California at Berkeley on an improved method—a ranking-referendum survey method that combines statistical econometric techniques with the methods and psychology of observer interviews. Ronald Wyzga, program manager, says plans are to test the procedure in field studies in 1987. □

SCENES: A Major Field Study of Visibility in the Southwest

EPRI, the Salt River Project, and Southern California Edison Co. are participating with federal agencies in a five-year field study of regional air quality and visibility in the southern parts of California, Nevada, and Utah, and northern and central Arizona. Called SCENES, this subregional cooperative electric utility, Department of Defense, National Park Service, and Environmental Protection Agency study is gathering and analyzing data from 13 observatories in the golden circle region of national parks and monuments that encompasses the Grand Canyon, Glen Canyon, and Bryce Canyon areas. Emissions in the region come from many point sources, including coal- and oil-fired power plants, copper smelters, and urban areas.





Operating since 1984, SCENES observatories conduct both long-term and short-term measurements intended to produce a comprehensive data set for studying the interplay of emissions, weather, and atmospheric processes with visual air quality. Additional data may become available from monitoring stations operated exclusively by the National Park Service and the California Air Resources Board.

so-called golden circle of national parks and monuments (Grand Canyon, Glen Canyon, Bryce Canyon, and Canyonlands national parks and the Death Valley and Monument Tree national monuments) where visibility is of great importance and where there are vast energy resources, mainly coal, as well as several large coal-fired power plants.

Although SCENES is a cooperative study, participants operate autonomously with their own contractors and budgets. EPRI's funding share is about $10 million over five years. Under contract to EPRI, AeroVironment, Inc., staffs two of the 12 SCENES observatories, performs data analysis and management, and coordinates filter-sample processing for all project participants. Also under EPRI contract, Environmental Research and Technology, Inc., provides external quality assurance and data auditing for all activities, while Combustion Engineering, Inc., acts as the overall SCENES program support coordinator and oversees the centralization of data provided by each of the participants.

SCENES includes both long-term routine and short-term intensive measurements as well as special measurements. The latter address specific methodological or scientific issues that are too complex for routine operations but that form a proving ground for new techniques and procedures. Data are now being analyzed from the first set of short-term intensive measurements, taken in late summer 1985, which recorded transport meteorology and aerosol distribution. They included special investigations of aerosol and light extinction measurement methods.

Last year the project began to address ground-based layered hazes during winter months. Researchers investigated the extent and persistence of winter haze in the Lake Powell region of Arizona and evaluated methods for measuring ammonium, nitrate, organics, and sulfate. The chemical composition of the aerosol was explored to determine which species appear to dominate. "The work indicates that what was previously thought to be localized haze actually extends for hundreds of miles. To characterize such haze will require measurements from aircraft and several ground stations" explains Mueller. "The puzzle is to figure out where the materials in the hazes come from. Do they all originate within each of the valleys, or do they come from other areas as well?"

Mueller says SCENES will rely to a great extent on emissions inventory and meteorology data from other studies. "Prior data are going to be tremendously useful, especially the emissions inventory EPRI is now completing under RAQS, which covers all source categories."

SCENES' specific objectives include a central data base of known precision; establishment of visibility and air quality climatology; determination of the fractional contribution of each type of aerosol material to visibility impairment; characterization of the optical properties of haze; and progress toward an ability to match visibility degradation to contributions from particular pollution sources. This last objective—source attribution—is the ultimate goal of visibility research.

"Although by itself SCENES is not intended to meet the ultimate goal, it will yield a greatly improved understanding of the problem and the information needed to solve it," comments Mueller.

SCENES research will benefit from EPRI evaluations of the existing mathematical source-receptor models, which aim to simulate and calculate the relationships between specific sources of emissions and nearby or remote observation sites. EPRI air quality modeling work that will be of use includes the plume model validation project, which focused on dispersion from smokestacks; continuing assessments of regional models and of the fundamental assumptions underlying their calculations; and studies to explore methods for identifying unique tracers or chemical fingerprints of specific sources of emissions far upwind from an observer.

SCENES is expected to provide the most detailed and accurate data base yet collected for testing those air quality models. "The results of SCENES will help validate or improve air quality models for research purposes," explains Mueller, "and will indirectly influence the setting of regulations."

It is in the regulatory arena that the results of ongoing research will eventually be applied. Particularly with issues of environmental protection, regulation often precedes a complete scientific understanding or a predictive capability. EPRI's visibility research, including participation in cooperative efforts with federal agencies and utilities, is contributing to improved scientific understanding and to more-informed regulatory decision making. ■

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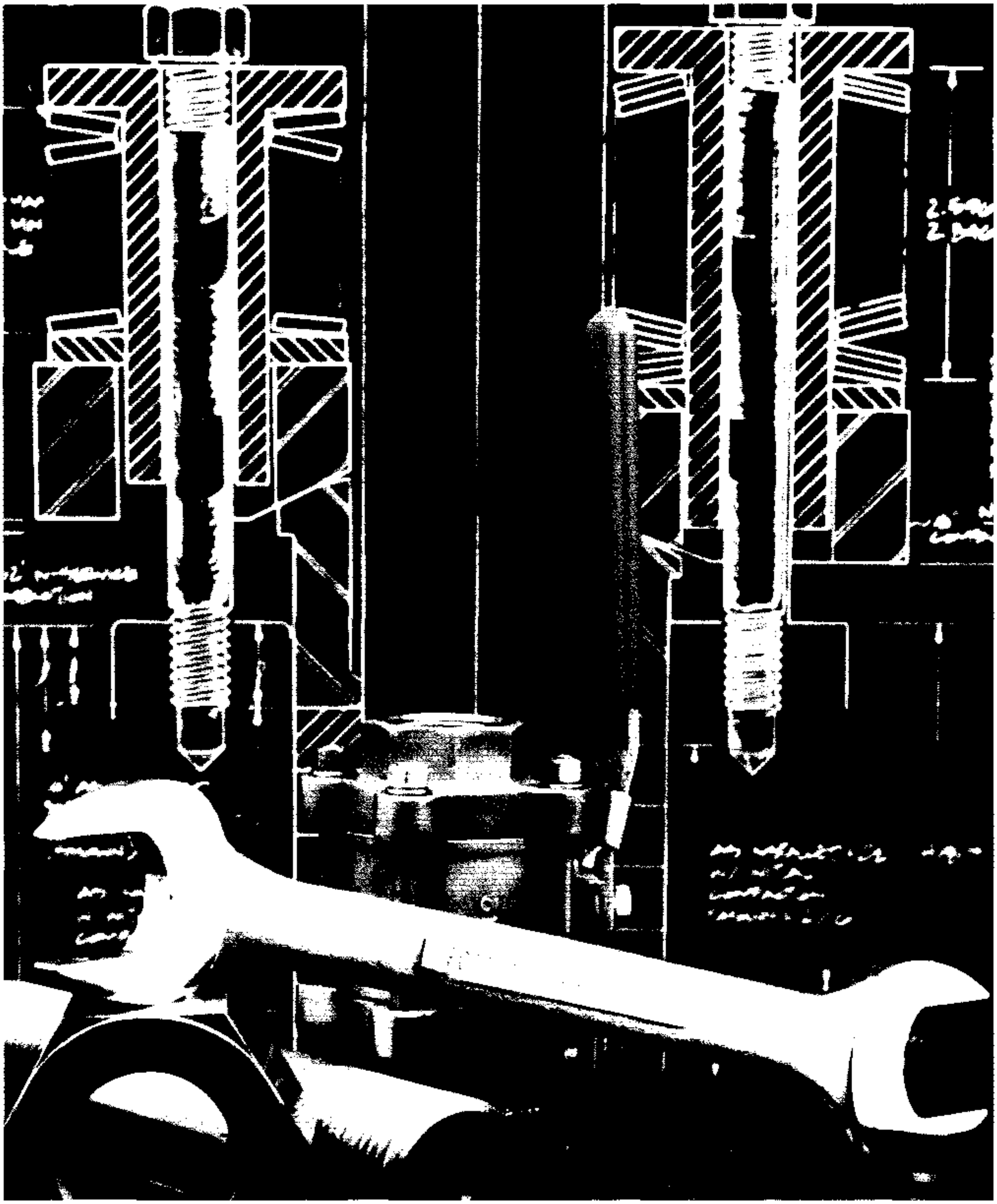
This article was written by Taylor Moore. Technical background information was provided by Peter K. Mueller, Environment Division. Additional information was provided by Mary Ann Allan, Robert Black, Glenn Hilst, and Ronald Wyzga, Environment Division.



MEAC

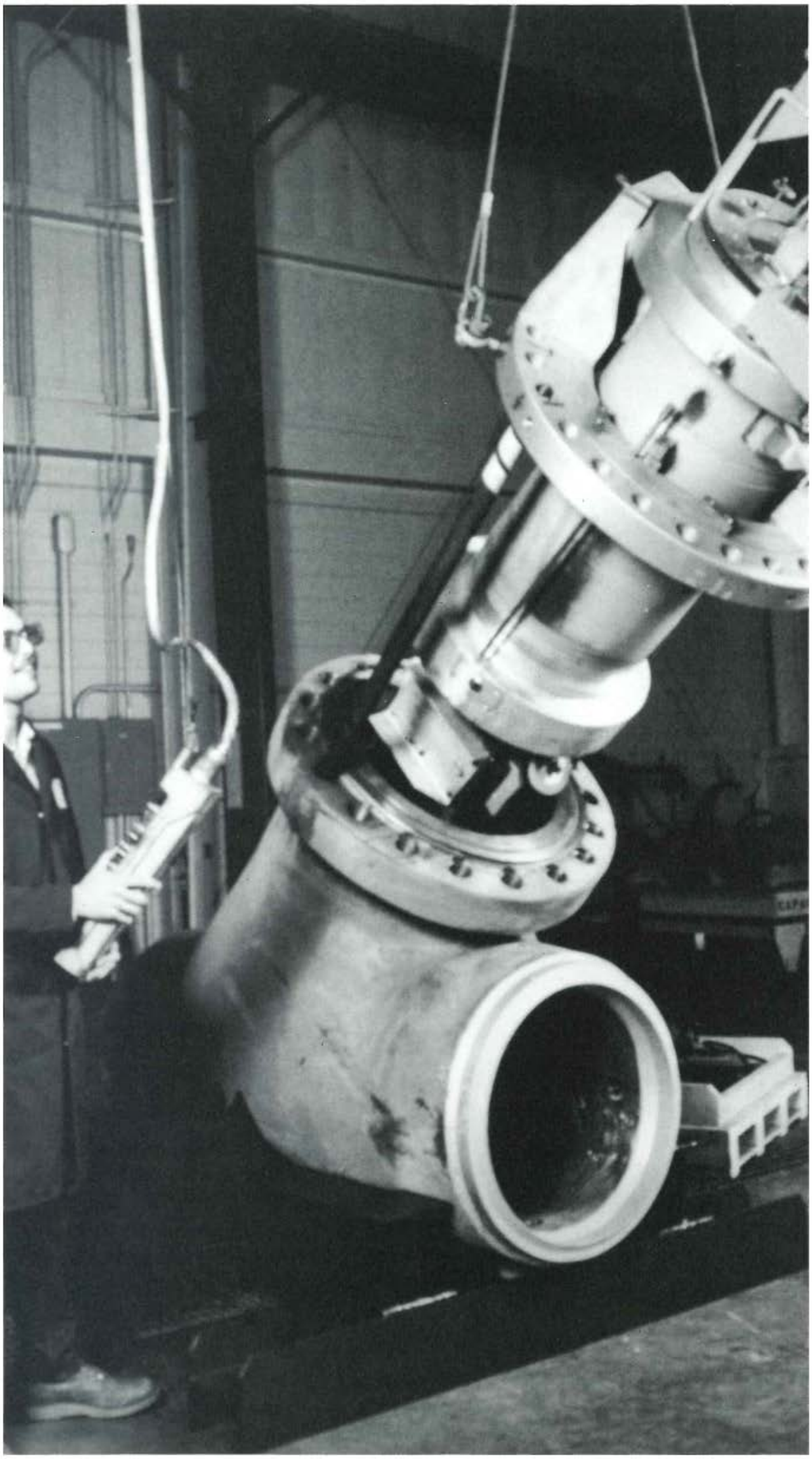
Speeding Transfer of Nuclear Maintenance Technology

The Maintenance Equipment Application Center, where utilities, researchers, and vendors meet to learn, evaluate, and demonstrate emerging technology, has become a focal point for technology transfer in the field of nuclear power plant maintenance.

Nuclear power plant maintenance involves difficult working conditions and costly, radiation-related problems that are unique in the utility industry. Researchers have steadily produced new tools, maintenance procedures, and plant improvements to solve these problems, but until recently utilities were hard-pressed to determine which of the solutions would prove most practical and cost-effective when put to use in a plant. In addition, utilities lacked a forum where they could discuss their maintenance problems, review different approaches, and get a hands-on introduction to maintenance equipment just emerging from the R&D pipeline.

In response to these utility needs, in 1984 EPRI established the Maintenance Equipment Application Center (MEAC) at EPRI's Nondestructive Evaluation (NDE) Center in Charlotte, North Carolina. Since its inception, MEAC has achieved steadily increasing participation from the utilities to support transfer of new or emerging nuclear maintenance technology from laboratory to power plant. In 1986 more than 40 nuclear utilities worked with MEAC in various ways.

MEAC achieves technology transfer through three principal methods: evaluation and demonstration of maintenance technology, workshops, and rapid response to individual utility requests for information and technical help. This program provides considerable flexibility, allowing utilities to direct their attention to those tests and workshops that match their individual needs. And if they desire, utilities can expand their involve-



Evaluating Equipment Performance

After testing hardware against performance specifications, the MEAC staff assembles mock-ups, including actual plant components, to test the technology under field-simulated conditions. Mock-ups are also used in special demonstrations for utility personnel. When the equipment is innovative and new to utilities, the evaluation process is sometimes expanded to include an in-plant demonstration.

ment in MEAC by hosting in-plant demonstrations of new equipment they find appealing.

The equipment chosen for technology transfer through MEAC is as diverse as the many different structures, systems, and components found in nuclear plants. Specific technologies range from tools for tightening bolts to sophisticated robotic devices. Certain high-priority areas of nuclear maintenance, however, such as the prevention of corrosion in steam generators or intergranular stress corrosion cracking in BWR recirculation piping, are covered by special EPRI programs apart from MEAC.

These special programs and MEAC share a goal of transferring technologies to the utility industry for solving generic maintenance problems. Equipment developed at EPRI is a natural candidate for transfer through MEAC, which serves as a window for the Institute's R&D products. In addition, MEAC evaluates equipment developed initially by other organizations and industries. Computer-aided design systems developed for electronics engineers, for example, are now being adapted to provide graphic displays of radiation fields inside plants.

"Rather than promoting any single product or approach, MEAC works to give utilities a wide and objective view of emerging solutions within important problem areas," says Howard Parris, EPRI project manager for MEAC. "By communicating with researchers and with each other, utilities use the center to determine the best solutions for their specific maintenance problems."

The economic push

Technology transfer in nuclear maintenance is driven primarily by economics. Although total plant savings are difficult to quantify, utilities can achieve substantial cost savings by improving the effectiveness and efficiency of maintenance and by reducing plant downtime. In part, the economic effect of maintenance on nuclear plant operations is a result of the sheer number of jobs and man-hours required to service the thousands of valves, hundreds of thousands of bolted connections, and miles of piping and wiring that must be kept in working order. Maintenance in a nuclear plant is such a large undertaking that reducing the man-hours needed for even a relatively simple task—adjustment of valves to control leakage, for example—can add up to a significant saving in direct costs.

Perhaps more significant, however, is the effect of maintenance on indirect costs related to plant capacity and availability. Because nuclear plants must be run according to technical specifications that are more strict than those involved in coal-fired plants, for example, higher levels of precision and rigor in maintenance are required. Pipe leaks, electrical failures in instruments, and many other malfunctions that might be overlooked or just temporarily patched up in a conventional power plant can force power reductions or shutdowns in nuclear plants. The shutdown of a single plant can cost from $500,000 to $900,000 a day for replacement power.

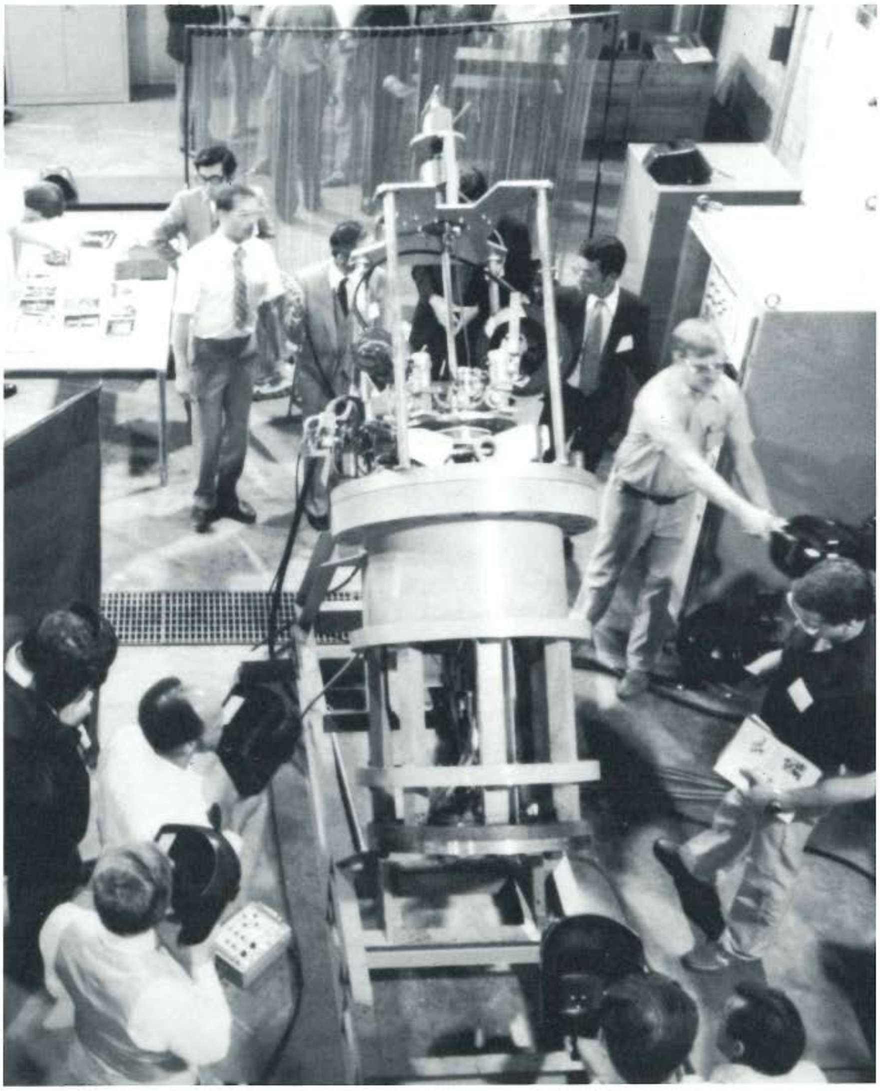
The economics of nuclear maintenance is also complicated by the presence of radioactivity in many areas of the plant. Radiation from an operating reactor makes it necessary to perform many maintenance jobs during outages. If any of these jobs can be finished more quickly, the utility can reduce both direct and indirect maintenance costs. In addition, utilities must follow guidelines and regulations that limit occupational radiation exposures (ORE) to maintenance workers. Reducing the time needed for such jobs as waste management, handling, welding, bolting, fuel changeout, and valve repairs can reduce ORE and enable utilities to deploy maintenance personnel more efficiently. ORE restrictions, for instance, often make it necessary to call in contractors to finish certain jobs or to use a large number of maintenance workers to do a job in many small portions. These are both costly practices that can also have a negative impact on job quality.

Testing in field conditions

When utilities set out to improve maintenance and reduce ORE they face added complications in the difficult working conditions that exist in many places in their nuclear plants. Recently, for example, several utilities encountered problems in the main steam isolation valves (MSIVs) that control the movement of steam out of the reactor core in boiling water reactors (BWRs). Research showed that attention to the hard-facing material on these large-diameter valves would reduce leaks and related maintenance.

The task of applying new hard-facing material with conventional welding equipment, however, was made extremely difficult by the location of the valves in the power plants. Maintenance crews could reach the valves only by leaning awkwardly inside the steam line or by reaching the valves from several feet away, using clumsy extensions on their welding and honing tools. As if these conditions were not difficult enough, the crews also had to do their jobs while wearing heavy protective clothing to guard against radioactive contamination. Acting like blankets that keep heat close to the skin, these radiation suits cover the entire body and limit a worker's productivity and dexterity. In the cramped and thermally hot conditions near the MSIVs, the suits made quality work nearly impossible.

Responding to these problems, MEAC organized a technology workshop in Charlotte to demonstrate remote equipment that could be positioned near the isolation valves, calibrated to perform a part of the task, and then activated after workers retreated from the area. In this technology, the Japanese were further along toward commercialization than U.S. manufacturers. Two Japanese machines designed specifically for the tasks were thus identified by MEAC and demonstrated on MSIV mockups at the cen-



An Industry Forum for Technology Transfer

Utility managers and maintenance people, researchers, and vendors meet at MEAC technology workshops to share experiences, exchange information, and get a hands-on introduction to new and emerging technology for nuclear plant maintenance. Focusing on specific areas of technology, the workshops combine seminar presentations with displays, demonstrations, and sessions where attendees handle the new equipment.

ter, along with existing American equipment that had been specially modified. Interestingly, the utility participants preferred the modified domestic equipment, which was smaller and easier to move and install in cramped conditions. As a result of this demonstration, several domestic vendors who participated in the demonstration were convinced they should proceed with the commercialization of new equipment for maintaining MSIVs.

In some cases, especially when a maintenance application is innovative and new to utilities, MEAC work may go beyond mockups and simulations to demonstrate the technology in an operating nuclear plant. Duke Power Co., for example, recently worked with MEAC to demonstrate the ability of a remotely controlled underwater vehicle to make inspections in the spent-fuel pool at the utility's Catawba station, Unit 1. Weighing less than 55 lb (25 kg) and equipped with color television cameras that send images back to the operators, these small, tethered vehicles were originally developed for use in the offshore oil industry. In 1984, however, as part of an ongoing effort to search other industries for potential nuclear maintenance applications, MEAC staff ticketed these vehicles for utility use.

"We first saw the vehicle in use in a demonstration tank at a MEAC technology session," explains David Parsons, a health physicist at Duke Power, who has helped his utility identify and implement maintenance technologies to reduce ORE. "Yet, we still needed to answer some questions specific to the plant environment. Basically, we had to see if the vehicle would send clear pictures back from our spent-fuel pool. Without demonstrating the vehicle at Catawba, we couldn't have gained sure answers."

After the vehicle passed through the demonstration without problems, Duke Power purchased a unit and has since used it to inspect spent fuel and related transfer and storage equipment in pools at its McGuire and Oconee plants. In addition, the utility has expanded its use of the vehicle, submerging it in the reactor vessel and hot leg pipe at McGuire for a brief in-containment inspection during an outage. Currently, Duke Power is providing feedback to the manufacturer to enhance the vehicle to more precisely meet power plant needs.

The path to commercialization

As well as helping utilities specify and acquire specially modified equipment, MEAC sometimes continues the technology transfer process by promoting the commercialization of maintenance equipment. "When making that final step from emerging technology to commercial product, we can significantly improve the availability and reduce the costs of technology to utilities," states Parris. "Commercialization is the culmination of our work at MEAC."

The commercialization process begins with the receipt of the equipment at the center, followed by laboratory tests to determine if design specifications have been met and to identify deficiencies or possible improvements. At the start of this test phase, MEAC staff work closely with the developer to learn about the capabilities and operation of the equipment. After this initial involvement, the developer sometimes works with MEAC on a consulting basis during further tests and demonstrations. At any point in the technology transfer process where modifications are found to be necessary—from bench testing to in-plant demonstration—MEAC will work with the developer to implement the changes. One surveillance robot, for example, was being demonstrated in a nuclear plant when researchers first saw the advantages of equipping it with headlights.

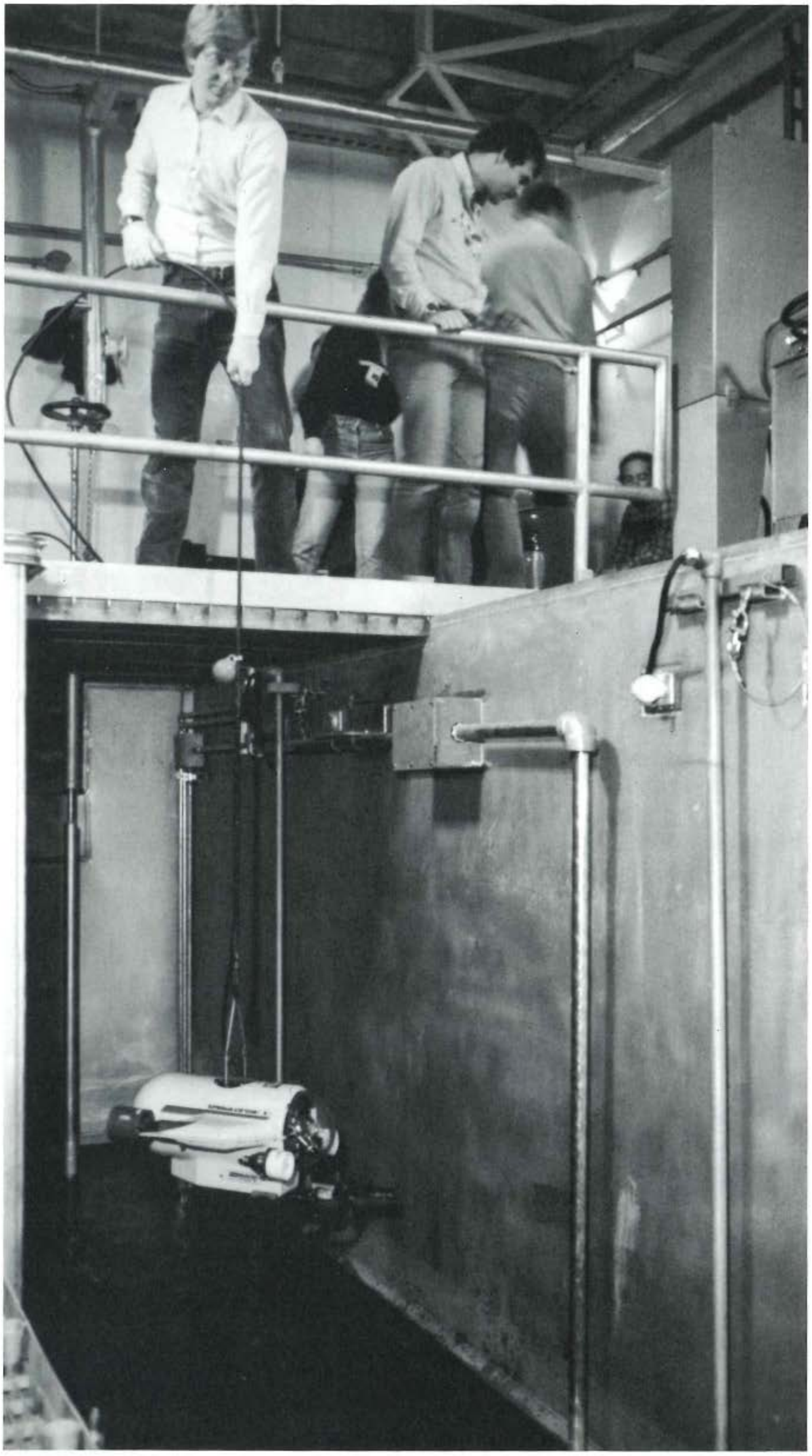
As the MEAC program matures, an increasing number of available products are resulting from the center's activities. A good illustration of the steps to commercialization was provided by the development in 1986 of a new device for lifting and moving the bulky, motorized drives on control rods in certain BWRs. Because these control rod drives (CRDs) were so difficult to handle, their maintenance changeout was contributing as much as 12 hours to scheduled outages.

After identifying the problem and soliciting utility suggestions for improvements, EPRI contracted with an engineering firm to design and build a simpler piece of CRD handling equipment—essentially a pneumatic winch mounted on a cart. Next, the winch was run through a series of tests to simulate its work on CRDs. After the equipment received excellent marks in this evaluation, a demonstration was held at the developer's site to let utility representatives see it in operation and familiarize themselves with the concepts involved in its use.

This laboratory demonstration was followed by a field demonstration at Commonwealth Edison Co.'s Quad Cities plant. In the meantime, however, the developer became convinced that the equipment would fill an important industry need. Even before the Quad Cities activity was under way, the developer contracted with EPRI to produce a commercial version of the equipment.

Technology from TMI

As an important part of the effort to promote technology transfer, MEAC is monitoring developments emerging from the recovery effort at the damaged Three Mile Island, Unit 2 (TMI-2) reactor in Pennsylvania. For the recovery, researchers developed equipment and procedures to help workers enter the thermally hot and radioactive environment in the containment building to inspect and sample the damaged core. In addition, recovery workers are using new technology to clean up and package core debris and other radioactive material from the containment and auxiliary buildings. GPU Nuclear Corp., DOE,



Response to Utility Requests

MEAC is always ready to answer requests from individual utilities for information on equipment sources and approaches to solving problems. In cases where a potential is perceived for wide-ranging benefits to the utility industry, MEAC may work with the utility on special equipment evaluations and demonstrations.

NRC, EPRI, and the Edison Electric Institute have all contributed to this work. Their efforts have already produced several technologies that can be modified and applied to improve maintenance in normally operating power plants.

MEAC has now collected information and devoted time at technology transfer workshops to several developments originating in the TMI recovery. These technologies include equipment for monitoring and managing ORE, improved diagnostic tools for electrical systems, robots for surveillance and sampling tasks, and programs for managing heat stress to workers.

Technology transfer between MEAC and the TMI recovery program goes in two directions. MEAC monitors developments from TMI, while managers in the recovery program look to MEAC for information on new technology. "In the recovery program, our workers used an ice vest developed by EPRI to keep from getting overheated in their protective clothing while working inside the reactor building," says Lawrence Balint, an industrial hygienist with GPU Nuclear, who participated in a MEAC technology session on managing heat stress in 1986. "Now, partly as a result of momentum created by the recovery, GPU Nuclear and EPRI are both at work on more comprehensive programs to control heat stress. Fortunately, MEAC is in place to help us learn from each other."

A meeting of industry minds

The many success stories issuing from MEAC share a common thread: improved communication between utilities and researchers. This type of two-way communication is the key to the program of technology workshops held at MEAC throughout the year. In each session, utility representatives and staff from EPRI and MEAC meet at the center for demonstrations and discussions of predefined areas of maintenance technology. Representatives from service companies and manufacturers are invited to attend if their participation is judged to be beneficial. The result is that utility people learn about available solutions; researchers get feedback to guide their future efforts; and vendors are exposed to industry needs and technologies waiting for commercialization.

Session attendance and agenda vary in size, depending on the scope of the problems being addressed and the range of solutions to be demonstrated and discussed. Seven utility representatives, for example, attended the 1986 demonstration on CRD handling equipment, an important application in only certain BWRs. By contrast, more than 90 representatives of utilities, service companies, and regulatory agencies participated in a 1985 session on pressure boundary bolting problems, an area of concern in nearly all power plants.

At the workshop sessions, participants are invited to witness demonstrations of the equipment under discussion and, in most cases, to try it out. Such hands-on activities vary with different sessions. Participants might handle a new hydraulic wrench, try on a vest filled with ice, or pilot a robot along a mockup of a plant manway. The events supplementing the demonstrations usually follow a workshop format, where participants can hear presentations, share experiences, and ask questions.

"We structure the technology sessions to communicate with both utility management and maintenance personnel," explains Ken Brittain, MEAC manager in Charlotte. "Managers can review the functions and the benefits of the new technology, while maintenance people can get a feel for the equipment and see how it works."

Rapid response to utilities

In addition to participating in technology workshops, utilities can make direct requests to MEAC for technical information and assistance. The center's bank of information on nuclear maintenance equipment has expanded along with its activities. As a result, the center staff can usually provide utilities with information to fill equipment needs, including lists of vendors and available domestic and foreign equipment.

To help keep the industry informed, MEAC is now negotiating with Electricité de France to create a catalog of maintenance technologies now in use in the French nuclear power program but not well known or available in the United States. This should help U.S. utilities keep pace in such areas as remote equipment and robotics, where the French are exploring unusual applications. In addition, MEAC is distributing a series of training videotapes to help utilities solve a series of problems related to bolting that have nagged the industry and even caused some plant shutdowns.

Sometimes, if a utility request for direct help is deemed to have value to the entire industry, MEAC will respond with an equipment evaluation or demonstration. For example, Duke Power's interest in remotely controlled equipment for handling filters sparked a MEAC investigation and demonstration of this robotics application in mid 1984. MEAC helped the utility identify vendor sources for the equipment, provided technical evaluation of the final bids, and then demonstrated the equipment under simulated conditions. Consequently, technology already in use by DOE was improved and then transferred to Duke Power and other utilities.

"At MEAC, we are looking for problems that need solving, as well as for solutions," adds Parris. "As more utilities participate in our technology transfer workshops and get involved in our tests and demonstrations, we see that no one has a monopoly on the problems, or on the good ideas." ■

This article was written by Jon Cohen, science writer. Background information was provided by Howard Parris, Nuclear Power Division, and Kenneth Brittain, MEAC Manager. Additional information was provided by Boyd Brooks, Richard Burke, and Floyd Gelhaus, Nuclear Power Division.

TECH TRANSFER NEWS

Washington State Uses ADEPT

Acid deposition policymakers encounter a minefield of scientific uncertainties, widely different value judgments, credibility issues, and political sensitivities. Public concern, however, has lent urgency to the examination of acid deposition issues, making it imperative that policy recommendations stem from competent, credible studies.

A textbook example of a credible, well-researched study started to take shape when the Washington State legislature responded to public and press concerns about the future of forests and fisheries. In 1984 the legislature directed its Joint Committee on Science and Technology to examine the potential for damage from acid deposition and to assess possible control options. At the same time, Puget Sound Power & Light Co. began its own acid deposition investigations. These two efforts came together in the study discussed below.

Compiling the data, of course, is central for such studies. Once this has been accomplished, the real challenge emerges: data analysis and interpretation. To be successful, the researcher needs a framework to order the mass of data into a clear picture, one that deals implicitly and explicitly with the scientific uncertainties and different value judgments inherent in a problem as complicated as acid rain. Faced with this situation, Puget Power turned to EPRI's acid deposition decision tree model, ADEPT, to address these concerns and enhance the technical studies that were under way.

The research focused on four major areas: sources and receptors, emission patterns, transfer functions, and control alternatives. Researchers incorporated a variety of other work into the input data for the ADEPT model. In addition, Michael Ruby, who worked on the state and utility studies, was familiar with ADEPT, which enabled him to design the study so the model could effectively deal with this input.

To identify sources, researchers examined emissions of sulfur dioxide and nitrogen oxide from coal-fired electric utility steam generating units, motor vehicles, industrial boilers, process heaters in petroleum refineries, and pulp mill furnaces. The current magnitude of the emissions and the economic trends in these industries prompted their selection for the study.

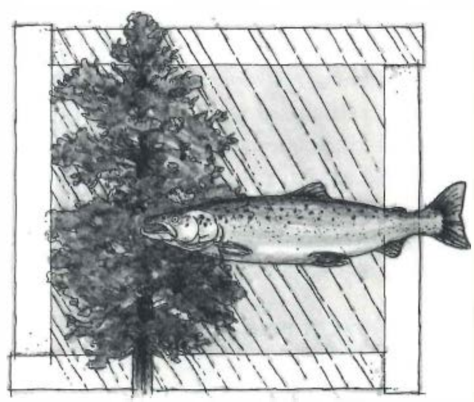
In addition, the research team used a model to project emission patterns in the study area, using analysis of such factors as expected world oil prices and coal demand. The meteorologic model based on the transport function was used to estimate future deposition patterns.

Resources believed to be sensitive to acid deposition were inventoried in detail, and four potential receptor areas were defined. The study concentrated on an area of 1.2 million acres for primary analysis, which contains 555 lakes and the headwaters of three salmon spawning stream systems. Within this area, over 121,000 acres of forest and 159 lakes were thought to be particularly sensitive to acid deposition because of the soil or the exposed bedrock characteristics.

Credible transfer functions (ways that emissions might travel from sources to receptors) were developed by examining meteorologic data for each season and by modeling atmospheric dispersion to establish how likely these routes were. These results were compared with current data on the deposition of sulfur dioxide and nitrogen oxides in rainfall in western Washington.

Finally, a reasonable set of control alternatives was sought—both currently available and/or likely to be technologically achievable within about 10 years. These included flue gas desulfurization for SO_2, selective catalytic reduction for NO_x, hydrodesulfurization of residual oil, and additional controls for motor vehicle emissions.

Once this considerable store of information was gathered, a group of experts, familiar with the state ecosystems, were interviewed to develop ranges for the variable uncertainties: How fast does sul-



fur convert to sulfate in air? How much sulfate originates from natural sources and how much is created by humans? How much nitrate is reduced by biologic activity before it gets into the river? The credibility of the study depended to a large degree on incorporating the range of the experts' responses to these and other uncertain variables.

At this point, ADEPT was to prove in-valuable to the study by providing a framework for examining conflicting opinions and doing the scientific bookkeeping. By incorporating uncertainties and the different value judgments of the experts, the model calculated the results of all the "what if" scenarios.

Employing decision analysis, ADEPT analyzes each alternative course of action, assigning probabilities to various outcomes at the points of uncertainty and figuring the expected economic value for each outcome. The model also shows the sensitivity of various results to changes in particular assumptions and predicts the value of new information. Thus ADEPT can calculate the likely cost/benefit of waiting for more research and can estimate the relative value of various research alternatives.

Use of ADEPT was particularly successful in putting the Washington data into perspective. The model was specifically designed for acid deposition policymaking, and Ruby cites the ease with which ADEPT can be customized to fit the specific situation. As Ruby observes, "ADEPT is an open program, extremely well written, and easy to use."

In 1986 the published report concluded that there is no significant acid deposition problem in western Washington and that imposing environmental controls would result in extremely high costs with very little benefit. These conclusions have been generally accepted, and the issue has been removed from the political arena. John Thielke of Puget Sound Power & Light Co. attributes the acceptance of these results in large part to the fact that the state legislature withheld making any decisions or commitments on acid deposition policy issues until completion of the study.

Contacts

John Thielke, Puget Sound Power & Light Co.; Michael Ruby, Envirometrics. ■ *EPRI Contacts: Richard Richels (415) 855-2602; Thomas Wilson (415) 855-7928*

Analyzing Radiation Effects on Lubricants

As time passes, lubricant originally tested and demonstrated with nuclear power plant equipment may no longer be available or may have been reformulated by the manufacturer. In choosing a replacement, engineers and maintenance personnel often must consider the effects of radiation, temperature, and use on different lubricants.

A new study, *Radiation Effects on Lubricants* (NP-4735), condenses data from an extensive literature search and the experiences of manufacturers, utilities, and expert individuals into a set of guidelines for choosing the right lubricant. Among the factors considered in preparing the guidelines were the relative radiation stability of various natural and synthetic base oils, classic additives, oxidation, and temperature sensitivity and the differences in radiation durability that depend on base fluid, additives, and the gelling agent (for grease).

Radiation effects on a broad range of materials are detailed in two earlier EPRI reports (NP-2129 and NP-4172M). A fourth, NP-4916, primarily for operations and maintenance personnel, will address such applications problems as the interchangeability of oils and greases within various use classifications, the compatibility of various products, and the estimation of lubricant condition. ■ *EPRI Contact: Robert Kubik (415) 855-8905*

Aqueous Discharge Monitoring Data Prove Valuable to PP&L

Pennsylvania Power & Light Co. used EPRI research to help establish more-reasonable wastewater discharge requirements for beryllium and selenium at its Montour plant. The utility was concerned that a new state procedure for controlling toxics in aqueous discharges could produce limits that were inconsistent with state-of-the-art monitoring capabilities, and attempts to measure exceedingly low limits could yield misleading (false positive) readings.

EPRI research helped PP&L understand this problem. Following negotiations with PP&L and others, the state decided to use the term *nondetectable* as the limit for some toxics rather than a single number. This wording gives PP&L an opportunity to use the EPRI data on permit compliance questions. If the state permit had included a specific number that was actually too low to measure, it could have been virtually impossible for PP&L to meet the permit requirement.

The EPRI data were developed by TRW, Inc. (EPRI CS-3741 and CS-3744). For the study, TRW first identified the most common pollutants in power plant discharges, including 11 trace elements of particular interest to the industry. Next, researchers identified and evaluated the EPA-approved or equivalent procedures used for measuring those elements in utility aqueous discharges. For each method, TRW determined the overall levels of reproducibility of the trace elements, and the limit of detection (measure of sensitivity of the test in detecting and identifying an element within the context of representative utility wastewater).

By using the results of this research, PP&L estimates a five-year levelized annual saving of $745,000. This represents EPRI's assigned contribution to reducing the probability of citizen suits or state noncompliance actions against PP&L. Also, the utility is using the data, together with EPRI's *Trace Metals Sampling and Analysis Reference Guide* (CS-3739), to refine effluent-monitoring methods and to guide analysts on the best available laboratory procedures.

As demonstrated by PP&L, utilities and government regulatory agencies now have a better technical basis for working together to establish monitoring requirements and effluent criteria for utility aqueous discharges. ■ *EPRI Contact: Winston Chow (415) 855-2868*

R&D Status Report
ADVANCED POWER SYSTEMS DIVISION

Dwain Spencer, Vice President

DIRECT COAL HYDROLIQUEFACTION

New developments at the Advanced Coal Liquefaction R&D Facility, Wilsonville, Alabama, demonstrate excellent progress in developing direct coal hydroliquefaction technology. On the basis of this work, it can be predicted that better utility-quality liquid fuels can be produced from coal at reduced costs. This 6-t/d hydroliquefaction facility, sponsored by DOE, EPRI, and Amoco Corp., is the only pilot plant still operating in the United States. The reduced scale of the project stands in marked contrast to the major internationally sponsored program that was carried out in the United States from 1974 to 1982 at a scale of 250 t/d at two sites—Catlettsburg, Kentucky, and Baytown, Texas.

From 1973 to 1982 efforts at the Wilsonville Process Development Unit were directed toward developing processes to produce solid solvent-refined coal (SRC) and liquid residual fuel oil. SRC and coal-derived residual fuel oil were expected to be compliance-fuel replacements for coal and petroleum residua, respectively. The progress and status of the research have been reported in several articles in the *EPRI Journal* and in many annual and topical reports. An excellent overview of Wilsonville progress was published in December 1985 (EPRI AP-4257-SR, Vol. 2).

The H-Coal and Exxon Donor Solvent (EDS) processes were brought to a state of commercial readiness by late 1982 through cooperation of DOE, EPRI, and a number of international, state, and industrial sponsors. EPRI's objective since 1982 has been to develop technology to increase the yield of the distillable fuels that are useful to utilities. The goal was to develop techniques that would be economically superior to the H-Coal, EDS, and SRC-II processes.

Significant improvements in process performance were achieved: for example, increased yields, selective production of utility fuel, improved product quality, and reduced hydrogen requirement. Table 1 indicates the progress made since 1982 and presents representative yields and qualities of the fuels produced from bituminous coals by the various processes.

In 1982 the H-Coal process represented the demonstrated state of the art. The 250-t/d pilot plant at Catlettsburg, Kentucky, produced 3.3 bbl of 20° API (American Petroleum Institute) gravity product per ton of moisture- and ash-free (MAF) high-sulfur bituminous coal. The boiling range distribution of the product made it particularly suitable for transportation fuels; however, further upgrading was required to bring the sulfur, oxygen, and nitrogen levels into compliance with commercial-grade standards.

The SRC II and H-Coal processes were very similar except that a catalyst was not used in the former. As a result, the product value from SRC-II liquids was significantly lower, and product quality, as measured by API gravity and heteroatom content, was much lower.

The latest and best performance was achieved at Wilsonville in 1986. It was the result of several stepwise changes (begun in 1983) to develop an integrated process that would produce a maximum yield of distillable product. The key elements in that evolutionary process were suggested by the results obtained in a number of small-scale experiments sponsored by EPRI.

The University of Wyoming conducted studies in which nondistillable liquids were used as solvent components; the mineral-matter-free liquids were derived from coal (AP-1079-LD). The results of this simulated single-pass, two-stage processing reaffirmed the importance of the nondistillable liquid recycle and emphasized the importance of effective hydrogenation of all solvent components. Yields of over 60 wt% C_4–850°F (454°C) distillate from bituminous and subbituminous coals presaged later results from continuous, integrated two-stage units.

Work by Mobil Research and Development Corp. showed that coal dissolution and conversion were facilitated by high boiling and nondistillable slurry oils and that a two-stage process, consisting of a thermal reaction stage followed by a catalytic stage, could be advantageous (AP-2912). These researchers further noted that the "overall effectiveness of a two-stage process is highly dependent upon successful operation of the initial stage." The hydrogenation catalyst was found to be effective in converting coal at mild hydrogenation conditions, even in poor-quality solvents.

The integrated, two-stage system—thermal first stage and catalytic second stage—was operated at Wilsonville during the 1983–1985 period. Kerr-McGee Corp.'s critical solvent deashing (CSD) system was used to reject ashy solids from the thermal first-stage reactor product stream. The net residual product was just adequate to transport ashy solids from the CSD system. That is, a practical method of nondistillable oil extinction was achieved and a yield of distillable product from bituminous coal of ~62 wt% MAF coal was possible.

Further ways were sought to improve yields and possibly to reduce process unit capital costs. The Mobil work suggested that the hydrogenation catalyst could be advantageous even in coal dissolution. That pioneering two-stage work reported important conclusions on condensation reactions, the efficacy of a two-stage process, and the use of catalysts.

- Condensation reactions must not only be considered as undesirable competitive processes that can occur during coal dissolution; they can also take place afterward at low temperatures. Further, some of the regression products must be considered more refractory than the structures in the parent coal because they are not reconverted to soluble products even after a high-temperature catalytic reaction.

- The overall effectiveness of a two-stage process appears to be highly dependent on the successful operation of the initial stage. The solvent quality and quantity are the determinant parameters (in the absence of added catalyst) in producing a dissolved coal product that is amenable to further conversion. Any

Table 1
TYPICAL PROCESS PERFORMANCE WITH BITUMINOUS COAL

Process	Configuration	Distillate (wt% MAF coal)	Yield (bbl/t MAF coal)	Distillate quality (gravity °API)	Nonhydrocarbons (wt%) S	O	N
SRC II (1982)	One-stage, noncatalytic	41	2.4	12.3	0.33	2.33	1.0
H-Coal (1982)	One-stage, catalytic	52	3.3	20.2*	0.20	1.0	0.50
Wilsonville (1985)	Integrated two-stage, thermal-catalytic	62	3.8	20.2†	0.23	1.9	0.25
Wilsonville (1986)	Integrated close-coupled two-stage, catalytic-catalytic	70	4.5	26.8†	0.11	<1	0.16

*Light product distribution, with over 30% of product in gasoline boiling range; less than 20% heavy turbine fuel.
†Higher boiling product distribution, with 20% of product in gasoline fraction and over 40% in turbine fuel range.

significant degree of regression either during the initial stage or between stages cannot be redressed by catalytic processing (at least not with the catalyst used in the Mobil work).

▫ A catalyst can dramatically increase coal conversion, even at low severity (as well as in a relatively poor-quality solvent). At the lowest severities, the presence of a catalyst improved conversion by about 20%. The role of the catalyst may be that of providing hydrogen through solvent hydrogenation and of directly interacting with the dissolving coal species.

▫ The presence of an active hydrogenation catalyst during the initial (short contact time) stage may significantly contribute to the viability of a two-stage process.

In 1984 planning and engineering began to pursue the possible advantages that had been suggested by the Mobil work—that is, to add a catalyst to the first-stage reactor (previously thermal) and to couple the reactors to avoid condensation reactions.

The revisions, consisting primarily of building a new expanded-bed reactor and coupling it directly to the one built in 1981, were completed in late 1985. The increase in distillate yield and the improved quality of the product were significant (Table 1). The effect of coupling the reactors was determined in early thermal catalytic operations in the new system. An increase in distillate yield of 3–4 wt% MAF coal was attributed to coupling alone. The yield increase that might reasonably be attributed to catalyst in the first reactor would be on the order of 5 wt% MAF coal. Unit capacity was nominally increased from 180 lb/h moisture-free (MF) coal to 260 lb/h MF coal by coupling the thermal catalytic system. The nominal capacity further increased to 300 lb/h MF coal when a catalyst was added to the first reactor.

Other improvements that are readily evident (but have not been evaluated fully) may also be noted. First, because there is no cooling and heating between reactors, the overall heat economy is improved. Second, because the pressure is not reduced between stages, the cost of mechanical equipment and pumping is reduced. And third, the reduced feed rate and better-quality feed make possible, respectively, a lower capacity (thus lower cost) and a more efficient CSD unit. These improvements were achieved by feeding Illinois No. 6 bituminous coal; however, similar improvements have been achieved in extensive work in which the feed was Wyoming subbituminous coal.

The advanced coal liquefaction system that has been developed is more efficient and more economic than the processes that preceded it. The current configuration has been in place only since November 1985, however, and considerably more work will be required to determine its optimal application. *Project Managers: William Weber and Norman Stewart*

GEOTHERMAL WELLHEAD POWER SYSTEMS

Two studies completed in 1986 explored two different approaches to binary-cycle power generation with modular systems. Both studies investigated power systems that would generate from 2 to 8 MW (e) net power with geothermal fluids at flow rates that could be obtained either from a single geothermal well or from two adjacent wells at temperatures ranging from 149 to 232°C (300–450°F). Previously, EPRI developed, built, and tested a wellhead-size rotary separator turbine (RST) power system that enhances the performance of the direct-flash power cycles, which are preferred for geothermal resources above 210°C (410°F). In both the two binary designs and the RST design, ways were found to use standardized equipment to cover a wide range of geothermal resource conditions.

Binary-cycle technology was selected for use with geothermal fluids in the moderate temperature range (149–210°C; 300–410°F) because previous analyses indicated at least a 20% better performance for the binary cycle than for the double-flash technique in this temperature range (AP-4070; ER-301). For the studies of the two modular binary power systems, EPRI chose to extend the temperature range upward to 232°C (450°F) in order to investigate the feasibility of using the binary approach with the higher temperature fluids that are more commonly used to drive direct-flash power cycles, where geothermal steam is the working fluid. In one of the modular binary studies, two hydrocarbon working fluids were used; in the other, the refrigerant R-114 was selected as the working fluid.

Before starting the two binary-cycle conceptual design studies, EPRI determined the performance that could be expected from power cycles optimized for maximum output per unit of geothermal fluid flow at selected, fixed resource temperatures between 93 and 316°C (200 and 600°F). The cycles analyzed were optimized for particular resource temperatures, and the best of 12 working fluids were selected for each of the temperatures considered in the analysis. These results were presented in a report (AP-4070) prepared for EPRI by United Technologies Research Center (UTRC).

The two new studies of binary cycles show that either design can result in performance at levels close to those expected from cycles custom-designed for a given temperature geothermal fluid.

The new designs use standardized equipment that can be shop-fabricated and delivered to the site as modules. The power systems can be installed at a prepared site in fewer than 60 days. The requirements of standardization, shop-fabrication, modular construction, and minimal installation time were among a list of desired characteristics that EPRI established with the two development contractors. Both contractors found that the desired characteristics could be met; however, each selected a different way to achieve the objectives.

Binary cycle designs

Under an EPRI contract (RP2195-4), a team from UTRC and the Elliott Division of United Technologies Corp. developed a design in which two hydrocarbon working fluids are used in a two-stage radial inflow turbine (Figure 1). The plant has a net output of 4.2 MW from a geothermal fluid at 190°C (375°F) and at a flow rate of 63 kg/s (500,000 lb/h). The working fluids are propane at temperatures from 149 to 168°C (300 to 335°F) and isobutane at temperatures from 168 to 232°C (335 to 450°F). A single gear and speed covers the whole range. Only the second-stage wheel and the inlet nozzle angles have to be changed to cover the temperature range. (The wheel would be trimmed to a smaller diameter when propane is the working fluid, and the nozzles would be set at optimal angles for the temperature at the user's site.)

The flexibility required in the remainder of the power system is obtained by using either of two types of heat exchanger in either parallel or series configurations of the standardized modules. One type transfers heat from the steam to the working fluid, as needed, when the geothermal fluid is produced by spontaneous flow with flashing in the wellbore.

The other type of heat exchanger transfers heat from a liquid source (i.e., hot water or brine) to the working fluid. This type of exchanger is required whether or not the resource fluid is flashed. It handles all the heat transfer if the resource fluid is produced with a downwell pump to keep the fluid in a single phase. It also handles the unflashed liquid and the condensed steam from the first type of exchanger if the fluid is produced by flashing.

The remainder of the power system consists of modular units for wet or dry cooling, geothermal fluid handling, electric power generation and switching, and system control. Field-erected wet-cooling towers are estimated to be slightly more economical than the shop-fabricated equivalent; however, the field-erected units could be used only if the system installation time is extended from 60 days to 120 days.

The second binary design, developed by Mechanical Technology Inc. (MTI), uses a single working fluid, R-114 refrigerant (RP2195-5). This design features a unique single-unit turbine-generator-feedpump that does not require an external lubrication system (Figure 2). The plant output is 6.7 MW net from a resource at 232°C (450°F), producing 63 kg/s (500,000 lb/h) of a steam and brine mixture. The turbine is a single-stage, radial inflow design, and the integrated unit runs at 60 Hz (3600 rpm) over the entire range of resource temperatures. It has a single shaft for all three rotors and uses the R-114 working fluid itself for lubrication and for cooling the generator. This design is used in two identical 1.1-MW units that have operated reliably since the summer of 1984 in a power system recovering 121°C (250°F) waste heat from a catalytic cracking unit at a refinery in California.

In this second wellhead power system design, the flexibility required to cover the 149–232°C (300–450°F) resource temperature range is obtained by changing nozzle angle, turbine wheel hub size, turbine wheel diameter, feedpump diameter, and generator frame size. With from two to five options for each of these variables of the integrated turbine-generator-feedpump unit, the MTI approach comes closer to being a customized design for each particular resource than does the UTRC–Elliott approach. The balance-of-plant design developed by MTI for the R-114 design also tends more to custom design by allowing the plant purchaser to select from among a range of standardized options for the heat exchanger, condenser, pump, cooling system, and electrical system modules. The standardization occurs more on the individual component level (e.g., an individual heat exchanger shell) than on a subsystem level (e.g., a module on which six heat exchanger shells are mounted and piped together).

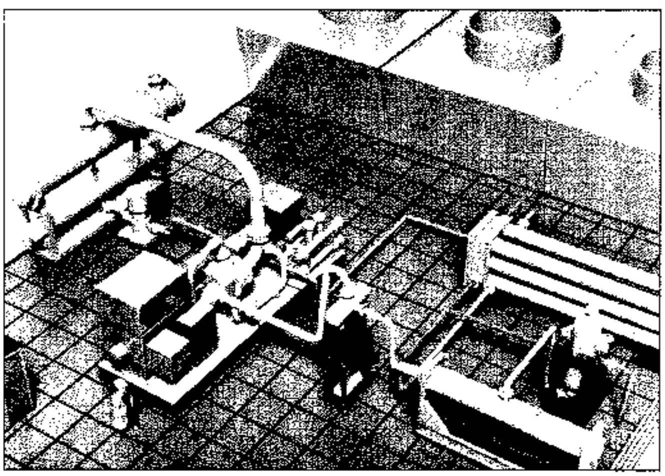


Figure 1 Model of the modular wellhead binary power system using hydrocarbon working fluid in the high-temperature configuration. The heat exchanger in right foreground takes steam from the separator (located between the two heat exchanger modules) and transfers heat to the hydrocarbon working fluid, condensing the steam. The condensed steam joins the separated brine going to the other heat exchanger module containing six brine-to-hydrocarbon heat exchanger shells. For lower temperature with pumped wells producing only brine, only the brine-to-hydrocarbon type (9.45 m) is used: two modules in parallel or series, depending on the resource temperature and flow.

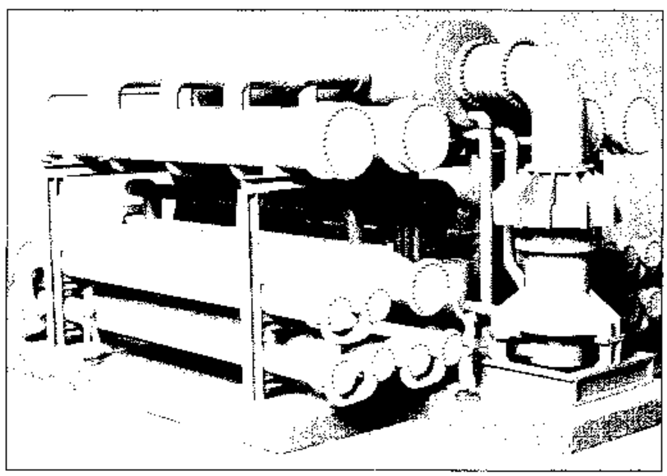


Figure 2 Model of the R-114 concept for a modular wellhead binary power system. The integrated turbine generator feedpump is at the right, mounted with the shaft vertical and the exhaust piping going out the top to a regenerator. The optional regenerator is mounted on the top of the central frame. A frame (or, in the high temperature case shown, two frames) alongside the central frame holds standardized heat exchanger and condenser shells (condensers on the top of the frame). An accumulator tank and condensate pump are in the central frame. The cooling towers are not shown. The regenerator measures 9.75 m long and 2.13 m in diameter.

Cost and performance

The two projects reached similar conclusions about the cost and performance of the two binary cycles. Over the middle section of the 149–232°C (300–450°F) range, both standardized power systems met the performance level of the custom-designed cycles presented in AP-4070: from 14.0 Wh/kg (5.9 Wh/lb) at 168°C (335°F) to 23.1 Wh/kg (10.5 Wh/lb) at 204°C (400°F). However, at the temperature extremes of 149°C (300°F) and 232°C (450°F), the performance of both of the standardized designs is about 20% below that of the optimal performance of the customized cycles.

The MTI design in which R-114 is used as the working fluid includes a regenerator in the design preferred for the high-temperature half of the range. The regenerator recovers superheat in the turbine exhaust and uses this heat instead of hot brine to supply the lowest-temperature heat input. This feature permits the estimated performance of the R-114 design to exceed that of the optimal custom-design performance: 29.3 Wh/kg (13.3 Wh/lb) for the R-114 design and 28.6 Wh/kg (13.0 Wh/lb) for the custom design at a resource temperature of 232°C (450°F).

The cost estimates of both contractors were the same: $900, $1150, and $1550/kW at resource temperatures, respectively, of 232°C (450°F), 190°C (375°F), and 149°C (300°F). These are installed costs on a net output basis, including an electrical substation; a 5-mile, 13.8-kV transmission line; and 25% for contingency and fee.

Role of wellhead plants

Identified geothermal resources are a significant resource base for power generation in the western states—some 23,000 MW for 30 years, according to the U.S. Geological Survey's 1978 estimate, which listed 52 geothermal fields. About four times this resource may exist in fields not yet identified. Fewer than 10% of the identified geothermal fields have installed generating capacity, and over 90% of the existing capacity is at The Geysers dry-steam field in northern California. Hot water (hydrothermal) resources constitute over 20,000 MW of the identified resource. These will produce single-phase hot water if pumped, or a two-phase flow of hot water (brine) and steam if produced by spontaneous flow. About 10,000 MW of the 20,000 MW identified hydrothermal resources are in the so-called moderate temperature range of 149–210°C (300–410°F).

To estimate the fraction of this resource base that would best be developed by using wellhead plants in the size range of 2–8 MW instead of larger, central plants in the 50-MW class, EPRI developed the data presented in Tables 2 and 3. Table 2 shows that small fields, defined as those estimated to support a generating capacity of less than 100 MW, constitute about 1200 MW (about 6%) of the identified hydrothermal resource base. These are fields likely to be developed with plants whose capacities are well below 50 MW because a 50-MW central plant would constitute such a large fraction of the estimated potential at the site that the possibility of the actual flow proving inadequate would pose an unacceptably high risk.

Table 3 shows a much larger potential market for wellhead power systems. Using the results reported in AP-4070 to estimate the power output of a typical well that produces geothermal fluid at a rate of 63 kg/s (500,000 lb/h), the table shows that about 4500 MW are in the resource temperature range between 150°C and 175°C (302–347°F). It is not likely that this potential will support a 50-MW plant, given the economic restraint on fluid transport, which dictates that all wells feeding a plant lie within a 2.5-km^2 (1-mi^2) area. Therefore, the largest potential market for small units of geothermal generating capacity will be at those sites with resource temperatures in the lower part of the moderate temperature range—say, 150–175°C (302–347°F). About 700 MW of the 4500 MW in this low-temperature group are also in the small-field group, that is, those having fewer than 100 MW (Table 2).

Although the low-temperature group and, to a lesser extent, the small-field group constitute the majority of the eventual market, small units are expected to be very significant as the means by which early development can occur at most of the fields not yet developed. Unless a fairly large number of wells are drilled and successfully tested before a power plant is built at a geothermal field, it is risky to invest in a 50-MW plant as the first unit. (At Heber, for example, where EPRI, DOE, San Diego Gas & Electric Co., and other sponsors built the 50-MW binary-cycle demonstration power plant, six wells were drilled and tested before the commitment was made to build the plant. The Heber binary plant is expected to require 13 wells to produce 50 MW net power output from the site's 182°C (360°F) resource.) Therefore, wellhead generating units, especially those that are standardized, readily transportable, and shop-fabricated, will play their most important role as the first units in new fields. The same basic power system can be used to gain experience with the production characteristics of new fields over a broad range of resource temperatures. Thus, wellhead units can become a familiar tool used by utilities and others to develop geothermal generating capacity. *Project Manager: Evan Hughes*

Table 2
SIZE OF IDENTIFIED GEOTHERMAL FIELDS
(hydrothermal only)

Reservoir Size Range (estimated MW, 30 yr)	No. of Fields	Total MW in Range
<50	18	575
50–100	8	649
100–200	6	842
>200	19	19,610
Total	51	21,676*

*The total would be more than 23,000 MW (e) if The Geysers, a dry-steam field, is included.

Table 3
FLUID-GATHERING AREA LIMITS

Resource Temperature Range (°C)	No. of Sites	Total MW (e)	Typical Temperature (°C)	Maximum MW per Plant*	MW per Well†
>300	1	3,400	316	253	15.8
250–300	5	4,561	260	157	9.8
200–250	11	6,886	204	86	5.4
175–200	10	2,300	182	59	3.7
160–175	15	1,225	165	48	3.0
150–160	9	3,304	149	40	2.5
	51	21,676			

*Assumes 16 wells per 2.5 km^2 (1.0 mi^2).

†Assumes 63 kg/s (500,000 lb/h) from each well.

R&D Status Report
COAL COMBUSTION SYSTEMS DIVISION

Kurt Yeager, Vice President

STEAM TURBINE ROTOR LIFE ASSESSMENT AND IMPROVEMENT

Steam turbine rotors must be highly reliable to avoid costly and potentially hazardous failures. Moreover, the reliability of these rotors is a key consideration in making repair/replacement decisions and in implementing programs to extend power plant life beyond the conventional 30 years. Ensuring high reliability requires improved methods to assess the remaining life of in-service rotors, improved rotor repair processes, and improved materials for new rotors to enhance performance during cyclic operation and under other higher temperature conditions. The key to meeting these needs is a better understanding of the mechanical and metallurgical behavior of rotors.

Steam turbine and generator rotors are among the most critical and highly stressed components of steam power plants. Rotor failure incidents have ranged in severity from a few catastrophic bursts to lengthy forced outages; all have imposed severe economic penalties on the utilities involved. Rotors made in the 1950s or earlier are of major concern because of their relatively poor quality.

According to recent industry studies, by the year 1990 turbogenerator units over 30 years old will account for 15% of the total capacity of the electric power industry and 75% of its reserve capacity. Under current life assessment procedures, most turbine rotors will probably be prematurely retired at the end of 30 years of operation. The development of more-accurate life assessment procedures, coupled with a greater knowledge of material properties, should permit a substantial extension of rotor life. A recent EPRI survey indicated that about 200 high-pressure/intermediate-pressure (HP/IP) rotors will reach the end of their design life during the next 10 years. If these rotors could be operated for another 10–20 years, the cost savings to utilities could amount to hundreds of millions of dollars.

The general objectives of EPRI R&D on steam turbine rotor life assessment and improvement are to develop (1) improved analytic methods for use in making run/repair/retire decisions and evaluating remaining rotor life, (2) improved rotor forgings capable of extended life and enhanced cyclic duty operation, and (3) analytic and experimental nondestructive examination (NDE) methods for evaluating the near-bore region and other critically stressed regions. Parallel R&D efforts to detect and assess cracking on-line are being conducted under RP1862-2. The objective is to develop a system based on advanced vibration signature analysis methods to assess the size and location of outside transverse rotor cracks.

Life assessment of in-service rotors

The useful life of rotors in service may well exceed the design life or fall considerably short of it, depending on design philosophy and related operational and metallurgical factors. Among the factors that tend to shorten life are residual stresses, stress concentrations, operating conditions not envisioned in the design (e.g., cycling or excessive operating temperature), a corrosive environment, and material degradation due to temper embrittlement, creep embrittlement, and other time-dependent phenomena. The relative importance of these factors is specific to each rotor—hence the need for a systematic methodology to assess the remaining life of in-service rotors.

Most scrapped rotors were manufactured during the early 1950s from forgings that had segregation bands of tramp elements, inclusions, and alloying elements. These elements and inclusions can promote the initiation and propagation of low-cycle-fatigue cracks during start-stop cycles. The low inherent toughness of the material leads to a high risk of abrupt failure due to cracking in both HP/IP and low-pressure (LP) rotors of this vintage. With HP/IP rotors other problems include creep and (because of improper or inadequate heat treatment) notch sensitivity and poor creep-rupture ductility.

One major source of uncertainty in assessing remaining rotor life is the lack of material properties data for rotors in the degraded service condition. Prolonged service exposure often leads to degradation of a material's fracture toughness, creep strength, and yield strength. Figure 1 illustrates the problem schematically. In the absence of any in-service toughness degradation of the material, the critical crack size (a_c)—the size at which unstable fracture occurs—remains unchanged, and a crack will grow from its initial size (a_o) to reach a_c at N_3 cycles. In actual practice, however, the toughness of the rotor may be degraded by temper embrittlement and other microstructural changes so that a_c is reduced and failure occurs after fewer cycles (at N_2). Moreover, service degradation may also adversely affect the rate of fatigue crack growth, resulting in even earlier failure (at N_1). Thus failure predictions based on the original, undegraded properties of the material could seriously overestimate service life.

The general principles of the methods and criteria used in making run/retire decisions for rotors are well known, but the details are normally proprietary to the equipment manufacturer. The methods are based on NDE, stress analysis, and material properties data. Using these elements, EPRI has developed the life prediction code SAFER (stress and fracture evaluation of rotors), with which utilities can independently evaluate remaining rotor life.

SAFER currently addresses one rotor failure mechanism: the growth of cracks from flaws near the bore as a result of low-cycle fatigue. The program performs a cluster analysis, searching the NDE data to locate defects predicted to link together by either ligament yielding or stress rupture. SAFER calculates the temperature and stress distributions in the rotor, determines crack growth during repeated cycles, and, on the basis of the material's fracture toughness, computes the number of cycles required for cracks to reach critical size.

In its present form, SAFER can be used to determine the remaining life of turbine rotors. Modifications are under way to enable the code to analyze generator rotors, perform probabilistic calculations of failure risk, and account for creep-fatigue crack growth in high-temperature rotors (RP2481).

Toughness degradation due to temper embrittlement is another mechanism that can affect the remaining life of both CrMoV (HP/IP) rotors and NiCrMoV (LP) rotors. A primary cause of this embrittlement is the segregation of certain impurities and alloying elements to the steel's grain boundaries. CrMoV rotors operate over the entire range of temperatures critical for temper embrittlement of that material (316–538°C). In extreme cases involving very high impurity levels, CrMoV steel has suffered significant embrittlement and fracture toughness degradation. NiCrMoV rotors generally operate below 370°C—in the lower part of that material's critical range (343–538°C)—and degradation may not be appreciable.

A new technique estimates the toughness of CrMoV and NiCrMoV rotors and disks by using Auger electron spectroscopy to determine the concentration of impurities at grain boundaries (RP559). The method also correlates the grain boundary impurity concentration with the material's ductile-brittle fracture appearance transition temperature (FATT) or with the increase in that temperature. (The FATT is the temperature above which the material is ductile and below which it is brittle.)

Another new method applicable to both CrMoV and NiCrMoV steels permits metallurgists to estimate the actual toughness of rotors and disks by testing a single Charpy specimen in the ductile-brittle transition region (RP2481-2). The method uses the quantitative relationship between the FATT and the percentage of the specimen's surface area displaying fibrosity.

Future R&D efforts in rotor life assessment will develop a materials data handbook, NDE procedures for the early detection of creep-fatigue damage, advanced techniques for estimating cyclic life expenditures, and improved rotor repair technologies.

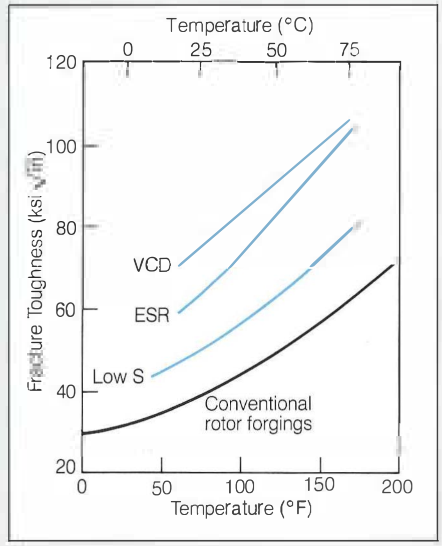
Life improvement of new rotors

Longer life for new rotors can be achieved by improving the toughness, creep strength, and low-cycle-fatigue strength of the CrMoV steels used in HP/IP rotors and the low-cycle-fatigue strength, toughness, and corrosion fatigue resistance of the NiCrMoV steels used in LP rotors.

The toughness of current CrMoV steels is relatively poor. Their FATT is normally well above room temperature; thus, to ensure ductility, during each cold start CrMoV rotors must be prewarmed to a temperature above the FATT before achieving full load. The prolonged startup and shutdown procedures required lead to higher capital and fuel costs and reduced operational flexibility. Such considerations have become especially important in light of the increased cyclic duty imposed on older fossil fuel units because of the use of nuclear units for baseload operation.

Improving the cleanliness of HP/IP rotor steels in order to improve toughness was studied by Westinghouse Electric Corp. (RP1343). Three processes for casting CrMoV rotor steel ingots were evaluated: electroslag remelting, low-sulfur silicon deoxidation, and low-sulfur vacuum carbon deoxidation. Heat-treated forgings produced by these processes underwent a metallurgical characterization that covered chemical homogeneity, sulfur distribution, segregation distribution, and internal material soundness. Mechanical properties were characterized in tensile, Charpy impact, fracture toughness, low- and high-cycle-fatigue, fatigue crack growth, and stress rupture tests.

Figure 2 CrMoV turbine rotor forgings produced by three advanced processes have shown greater fracture toughness than conventional forgings. The processes are low-sulfur silicon deoxidation (Low S), electroslag remelting (ESR), and low-sulfur vacuum carbon deoxidation (VCD).



Both the metallurgical and mechanical properties of the three advanced rotor forgings showed substantial improvement over the average properties of 29 rotor forgings produced during 1971–1977 by means of conventional steel-making technology. The new processes reduced sulfur content by a factor of 5 to 10 and phosphorus content by a factor of 2.5 to 6. Hence the fracture toughness of the advanced forgings was considerably higher than that of conventional forgings (Figure 2), resulting in increased critical crack size and providing better assurance against brittle failure. The new forgings also exhibited moderately improved creep rupture strength and low-cycle-fatigue resistance, which promise extended life and enhanced cyclic operating capability.

The three rotors manufactured during the evaluation have been installed at Oklahoma Gas and Electric Co., Southwestern Electric Power Co., and Southwestern Public Service Co. Since this evaluation, Westinghouse has incorporated the new processes into its standard product line; as of May 1986, it had manufactured over 40 rotors by these processes for installation in both new and retrofit utility steam turbines. *Project Managers: Thomas McCloskey, Ramaswamy Viswanathan, and Robert Jaffee*

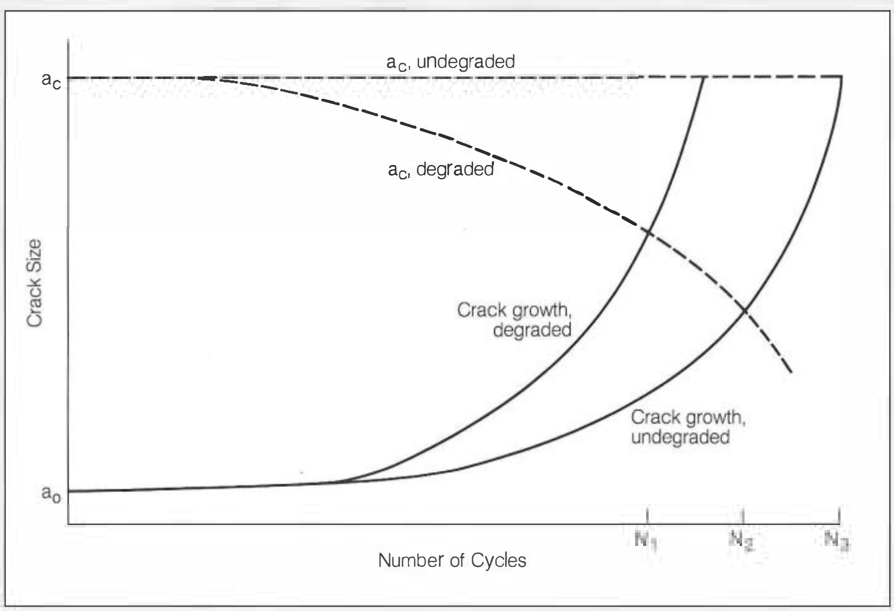


Figure 1 In-service degradation of turbine rotor material can increase the rate of fatigue crack growth and decrease the critical crack size (a_c), the size at which fracture occurs. Thus, in degraded material, a crack with an original size of a_o could reach a_c at N_1 cycles, causing failure before the expected life of N_3 cycles.

R&D Status Report
ELECTRICAL SYSTEMS DIVISION

Narain G. Hingorani, Vice President

DISTRIBUTION

Emergency operating temperatures for extruded cables

The behavior of extruded dielectric distribution cables insulated with cross-linked polyethylene (XLPE) or ethylene-propylene rubber (EPR or EPDM) has been studied for several years at Cable Technology Laboratories, Inc. (RP1516); progress reports have appeared in earlier status reports (e.g., *EPRI Journal*, September 1983, p. 45). It is clear from this earlier work (performed with new or previously unaged cable) that the behavior of the cables under thermal overload is not limited by the response of the extruded insulation to the thermal stresses. Indeed, the earlier work demonstrated that the electrical insulation is quite capable of withstanding over 300 daily load cycles to a conductor temperature of 130°C (industry specification requirements) and even greater. These results were presented at the IEEE–PES 1984 Transmission and Distribution Conference in Kansas City.

The results, which were considered surprising at the time, generated additional questions.

□ What would happen if the cables had been aged several years in the field and thus possessed water trees to a substantial degree? Would they still be able to withstand a 130°C conductor temperature, or would they fail under thermal overload conditions? Almost certainly the cables would undergo thermal overload only after aging, not immediately after installation.

□ What would happen if the emergency overload conditions were longer than a working day (the original study plan)—for example, for an unusually long outage, such as 10 days?

□ What if the temperature rose at a faster rate than that studied on this project; for example, what if the temperature rose from 50°C to 130°C in 15 min rather than over a number of hours?

The answers to these practical questions were considered essential before the earlier phase 1 results could be accepted with confidence. Accordingly, with the cooperation of two major U.S. utilities, several hundred feet of large-conductor, service-aged cable were obtained and tested in three sets of experiments designed to answer these questions.

Both cables for the work were insulated with XLPE. Cable 1 (750-kcmil stranded Al conductor, cross-linked conductor shield, 175-mil insulation, and polyethylene insulation shield) was service-aged for 11 years as part of an in-duct three-phase system. Cable 2 (1000-kcmil stranded Al conductor, cross-linked conductor shield, 175-mil insulation, and polyethylene insulation shield) was service-aged for 14 years as part of a feeder system installed at a crossroad. All cables had concentric neutral copper wires, were steam-cured, and exhibited substantial water treeing when examined before testing.

For the first experiment, the cables were subjected to 10 and 101 daily load cycles. Test results demonstrated that although the cables had reduced ac and impulse breakdown strength relative to unaged cable (as expected), they did not undergo a further decrease on 101 load cycles regardless of whether the load cycling took place in an air or water environment. This indicated that water tree–containing, service-aged cables are not harmed by thermal overload. In fact, the ac breakdown strength was observed to increase; this is presumed to be a result of the thermal treatment's ability to drive off the water and collapse the voids or imperfections believed to develop on service aging (Figure 1).

The second experiment, a long (300-h) continuous thermal overload, also led to an increase in ac breakdown strength when the cable was tested at the 130°C overload tem-

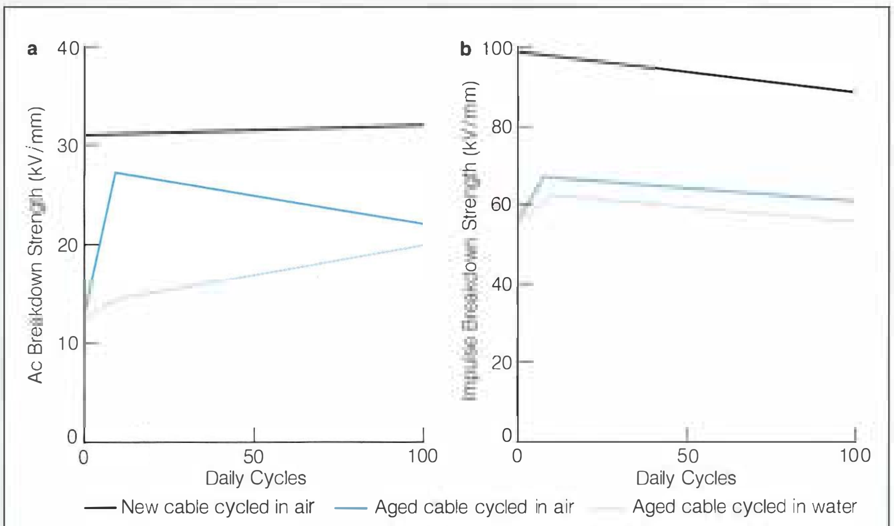


Figure 1 Ac and impulse breakdown voltage stress at 130°C versus number of daily load cycles for 15-kV XLPE cable. Graph (**a**) shows that when cable is removed from the earth and subjected to thermal overload (10–101 daily cycles to 130°C conductor temperature), the ac breakdown strength of 11-yr field-aged cable increases. Graph (**b**) shows that testing the same cable to thermal overload after removing it from the field results in no significant loss of impulse strength. In both cases, one might have expected a drastic drop for water-treed cables; surprisingly, this phenomenon did not occur.

perature. The third experiment, the rapid rise test, also showed an increase, although not as great as that for the long overload.

In general, rather than causing a further reduction in cable breakdown strength, these thermal overload treatments induced an increase (probably because of moisture and volatiles being driven out). It is equally important to note that no cable ever failed during this work or during phase 1 work. This performance indicates that the voltage/thermal endurance of the extruded cables under these conditions is excellent.

Several other conclusions can be extrapolated from these results. (1) Because the voltage/thermal endurance of these cables is so good, the limiting factors on cable thermal overload capabilities are the accessories and the compatibility characteristics of the insulation shields. It should be noted that these older service-aged cables all had thermoplastic shields (a less common construction today), and as long as contact at the shield-insulation remained, behavior was adequate. Conventional thermoplastic insulation shields should not be employed with cross-linked insulation where thermal overload is possible or more probable (e.g., feeder cable). (2) The use of thermal stress to accelerate aging under dry conditions does not lead to an accelerated loss of life, as occurs under wet conditions. These extruded polyolefinic cables do not respond the way cellulose insulation does.

This work set out to establish the thermal overload capability of extruded cables, and that task has now been accomplished. These results were presented at the IEEE–PES 1986 Transmission and Distribution Conference in Anaheim, California. These results have additional implications for cables in service that are thermally aged in the dry state. Hence, for example, based on knowledge of material properties, total insulation composition (cross-linking agent, antioxidant), and thermal conditions, better understanding of degradation mechanisms and more-reliable life estimations may be possible. *Project Manager: Bruce Bernstein*

Advanced tree-trimming equipment

Electric utilities must trim trees to maintain proper line clearances as a means of preventing service interruptions. An estimated half-billion dollars is spent every year on tree-trimming activity. Because tree trimming is so labor intensive, any saving in labor could result in a substantial saving in cost to utilities.

An earlier EPRI study determined that tree-trimming productivity could be improved by reducing the amount of time required to set up for a cut (RP1780). The current project seeks to develop advanced tree-trimming equipment that will reduce set-up time (RP2358). The goal is to increase labor productivity 20% or more.

Figure 2 Artist's concept of a pantograph-supported telescopic boom pole saw that can be used to speed tree trimming in utility rights of way. The device can reach limbs that are on the other side of a 10-ft (3-m) crossarm.

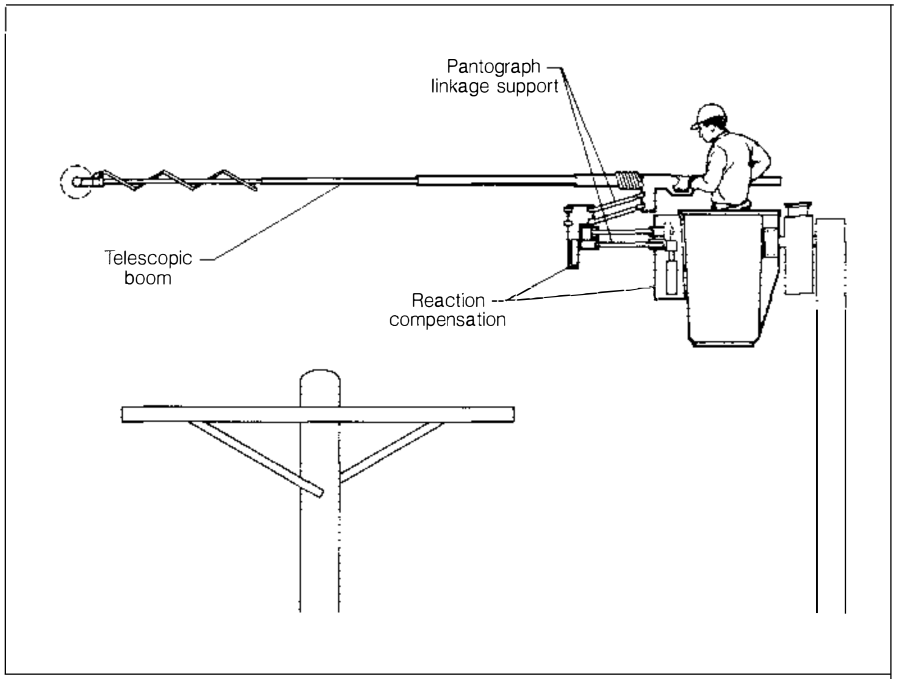


Figure 2 shows the concept of the equipment being developed, a pantograph-supported telescopic boom pole saw. This equipment consists of a three-section boom that can extend from 5 ft to 15 ft (1.5–4.6 m), at the end of which various tree-trimming tools can be attached. A circular saw, a pruner, and a chain saw are all likely candidates. A wrist rotation action is provided between the tool and the boom to facilitate making a cut flush with the tree trunk.

This equipment has the following advantages.

- The boom can reach into areas inaccessible to tools held by a person in a bucket truck.
- The equipment can reach into the heart of a tree to cut major limbs without cutting an opening for the entry of the bucket.
- The equipment can trim a larger area from a given bucket location.
- Positioning the boom is quicker than repositioning the bucket, the speed of which is limited for safety.

The pantograph-supported telescopic boom and cutting tool are expected to weigh 130 lb (59 kg) or less, but the operator will not support more weight and torque than when using a 6-ft (1.8-m) hand-held boom. The equipment is expected to be cost-effective and is designed to be retrofit onto an existing bucket truck. Power for the boom and tree-trimming tools will be supplied by the existing hydraulic tool circuits on the bucket truck.

The final design for the equipment has just been completed. The contractor is seeking suppliers for the various components needed for the device. When the pantograph-supported boom is assembled in mid 1987, it will be field-tested by two utilities to prove the labor savings possible. *Project Manager: Harry Ng*

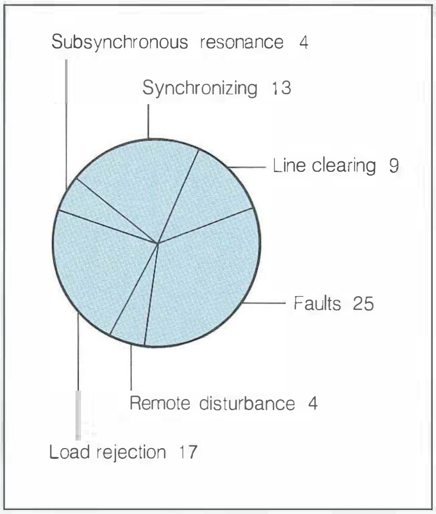
PLANT ELECTRICAL SYSTEMS AND EQUIPMENT

Field monitoring of generator shaft torsional vibrations

All but one of the torsional vibration monitoring systems (TVMSs) have been installed and commissioned in power plants of utilities participating in this project (RP1746). The remaining TVMS is scheduled for installation in a nuclear power plant that has been postponed indefinitely. This brings to 15 the total number of turbine generator shafts being monitored in this project.

A microcomputer workstation provides the necessary analytic support for the monitors. Workstation use has permitted closer control and management of the data base and event analysis. Although only 72 events have been

Figure 3 Distribution of turbine generator and transmission system interaction events.



captured to date, this sampling has demonstrated to the industry that the various interactions on these units are not severe enough to cause shaft fatigue damage (Figure 3).

EPRI has initiated another project to capture generator-system interaction data for determining generator electrical transient characteristics (RP2308-3). Adding shaft speed signals to the quantities being monitored in the new project will make it possible to determine the shaft torsional response to system events. The same microcomputer workstation will service the data from both monitors. A larger statistical sampling will be available for the shaft torsional fatigue studies when the data from these two groups of monitors are combined. *Project Manager: James S. Edmonds*

TRANSMISSION SUBSTATIONS

PCB residue in transformer carcasses

By EPA regulation, the only means currently permitted for disposing of an askarel transformer requires draining and rinsing, followed by incineration of the fluids and disposal of the carcass in a certified landfill. The liability for the carcass remains with the original owner, and it is possible that such landfills could become Superfund sites, with attendant costs and problems. If detanking a transformer were permissible, the cellulose material could be separated from the metals. This process could be followed by incineration of the PCB-impregnated cellulose material and cleaning the metallic parts and tank to whatever specification is required for routine salvage or disposal. Because removing PCBs from the environment is in the public interest, EPA has granted an experimental permit for laboratory procedures to establish a workable process. The overall benefit to utility owners of askarel equipment could be significant.

In RP2028-19 General Electric will establish the level of PCBs remaining on metallic surfaces of transformer carcasses after typical cleaning. The cleaning operations to be used are flushing, bathing in an ultrasonic bath, and spraying, or combinations, using trichlorotrifluoroethane (R113). A number of small transformers exemplifying larger network transformers will be torn down and cleaned, and wipe samples from the various surfaces analyzed. The results of these analyses will be used to estimate the amount of PCB residue in transformers after cleaning and determine the suitability of landfill or other alternatives for ultimate disposal of the noncombustible solids.

In a related area, EPA has also indicated a need for experimental information to evaluate the change in PCB level in dielectric fluid after retrofilling. EPA initially suggested a statistical study to determine the effects of time and loading-cycle temperature on distribution of the remaining PCBs between the transformer solids and the replacement fluid. It now appears that we have the opportunity to gather more basic data on this distribution by careful attention to analyses and material balances of fluid components in the course of this project.

For retrofill information, the percentage of original fluid remaining in a transformer after draining and flushing will be determined experimentally for at least one size of askarel transformer (10 kVA). Estimates will be made for other sizes and designs of transformers. A number of small transformers that have PCB-contaminated mineral oil in the 50–1000 ppm range and have had the fluid mixture achieve long-term equilibrium will also be torn down. A careful material balance for fluids in the cellulose and the free oil will be made. The PCB-oil mixture will be extracted from the cellulose and analyzed for PCB-oil ratio in parallel with the analysis of the bulk fluids.

If there is no change in composition of the oil mixture from saturated paper to bulk oil, we can safely predict the maximum PCB content of the retrofill. This will equal the concentration of PCBs in the bulk oil before retrofilling multiplied by the percentage of oil held up in the transformer. This maximum will hold under any cycling temperature condition and infinite cycling time. One precaution required will be the determination of the range of fluid volume expected to be held up in the transformer core. We have been assuming 2–5%. What is the expected maximum? Can it be isolated to certain transformer models and designs? An upper limit must be determined; laboratory work on this project started in October 1986. *Project Manager: Gilbert Addis*

POWER SYSTEM PLANNING AND OPERATIONS

Economic dispatch and power plant performance

Increasing labor and equipment costs, as well as less-reliable fuel supplies, make it mandatory to demonstrate new techniques for improving the performance and dispatch of existing fossil fuel power plants. In response to this situation, EPRI's Coal Combustion Systems and Electrical Systems divisions undertook a large joint project (RP1681, RP2153) as a single research and demonstration project for the industry.

Potomac Electric Power Co. (Pepco) was selected as the host utility and prime contractor. The host generating unit, Morgantown Unit 2, is a coal-fired, supercritical once-through unit with an electricity output of 575 MW, which was placed in service in 1971. Combustion Engineering, Inc., supplied the boiler, and General Electric Co., the turbine generator unit. The Morgantown plant and Pepco's system control center are serving as test facilities to determine the value of instrumentation enhancements, increased computer use, plant modeling improvements, modifications in plant control and operating procedures, improved data transfer between the power plant and the energy control center, new or improved plant models for use in system planning and operation, on-line heat determination, and enhancements to system economic dispatch and unit commitment.

A team of 27 experts from other utilities are acting as industry advisers to the project. A three-day workshop was held in Washington, D.C., in November 1986 to report the results of recent work to the industry.

Earlier project work involving electric system operation included research to determine the effects of errors in incremental heat rate curves on the economic dispatch process. The earlier work contributed the following.

□ Determined the effects of input/output and fuel cost uncertainty on overall production cost

□ Provided an error analysis of the present testing methods for unit performance related to scheduling and dispatch

□ Determined the best method of modeling unit input/output functions and selected the best algorithms for scheduling and dispatch to minimize production costs

Errors in calculating incremental heat rate curves for economic dispatch can result in incorrect generation allocation and increase operating costs by increasing fuel consumption. From studies on the Pepco system, it appears that the fuel cost penalty becomes significant for incremental heat rate errors corresponding to performance measurement uncertainty above 4%. At error levels corresponding to 6% performance measurement uncertainty, the expected fuel cost penalty was approximately 0.3% of Pepco fuel cost for the October 1982 period of simulation.

In more recent work researchers determined the candidate dispatch algorithms, requirements for transfer of data between the dispatch control center and the power plant, display requirements, and performance indexes to help dispatchers and plant operators assess system status and plant performance.

Work on candidate dispatch algorithms had these objectives.

- Define system performance and determine good system performance
- Determine the cost-effectiveness of improving the existing automatic generation control/economic dispatch (AGC/ED) control systems and determine the time frame in which the corrections should be made
- Identify improved algorithms not widely used but effective in improving information available from increased plant monitoring
- Determine cost-effective modifications to current AGC/ED systems that are practical within the present state of the art

Researchers determined that three components were essential in a modern AGC system: a short-term load predictor, a dynamic dispatch algorithm, and a coordinator between the load frequency controller (LFC) and the dispatch algorithm (ED).

The short-term load predictor requirements include a 2-h-ahead prediction with twenty-four 5-min predictions within the 2-h period. The dynamic dispatch algorithm uses the dynamic programming successive approximation approach. The frequency-domain partitioning method developed by Philadelphia Electric Co. (Peco) was used for the coordinated controller.

Software previously developed by Systems Control, Inc., and Wisconsin Electric Power Co. for a DOE project, as well as the previous work by Peco, was used as the basis for the software. The three components were incorporated in a test bed by using EPRI's area control simulator program (RP1048). A set of performance criteria were selected: (1) root-mean-square (rms) value of the area control error (ACE), (2) maximum instantaneous ACE, (3) rms value of the system frequency deviation, (4) maximum instantaneous system frequency deviation, (5) total unit movement without regard to direction for all units in the system, (6) total number of unit reversals for all units in the system, and (7) total production cost for the system.

Although not optimized or tuned, the results indicated the value of such an approach. Compared with the conventional lambda dispatch, the total unit movement and the total number of unit reversals were each reduced by more than a factor of three, and the production cost was reduced by up to 0.3%. Future work will continue to develop an improved AGC simulator and to determine cost savings that would result from the use of improved AGC/ED algorithms.

The data transfer and display work resulted in recommendations for data transfer and display to dispatchers, data transfer to dispatch computers, data transfer and display to unit operators, and other recommendations pertaining to education and identification of personnel on shift. These recommendations were developed after on-site interviews with dispatchers, unit operators, and supervisors at six utilities.

Performance monitors are support tools for dispatchers and unit operators to help assess system status and unit performance. Performance monitors can be divided into three categories: economic (periodic performance tests, off-line/on-line performance calculations), forecast (load forecasting, unit availability), and control (operating reserves, transfer capability, inadvertent interchange, and time error). Performance monitoring is usually based on a comparison between actual performance and a performance expectation. This segment of the work summarized the performance monitors available for use in both the control center and the power plant.

A survey of the utilities that have representatives on the project advisory team recommended that the incremental heat rate curves should not be modified more than once an hour because of power transactions between utilities and the effect of the incremental heat rate on the transaction price. An exception is allowed when a major change in unit performance occurs.

Other project work includes boiler performance optimization, turbine cycle monitoring, and overall unit heat rate determination. *Project Managers: John Lamont, Electrical Systems Division, and Robert Leyse, Coal Combustion Systems Division*

Direct stability analysis

For many years researchers have attempted to calculate power system stability with a direct method based on energy balance concepts. In theory the calculation of stability with the direct methods should not take more than two load-flow solutions—many times faster than present methods—and provide useful new information. These features of the direct stability method may make possible several much-desired applications, such as on-line stability limit calculation and quick screening of networks for stability problems. Until several years ago, however, direct calculation methods failed when applied to anything but unrealistically small and simple power system models.

Since 1983 researchers at Ontario Hydro and Iowa State University have worked toward demonstrating feasibility and applications of the transient energy function (TEF) direct stability analysis method in large-scale networks (RP2206-1). The software developed earlier in RP1355-3 was improved and expanded to accommodate 1500-bus, 300-generator networks. Researchers then used a series of six realistic test cases of increasing size and complexity to test TEF method accuracy, speed, and reliability. They compared results of test cases with traditional simulation results to verify proper TEF method execution. Investigators invented or adapted numerical analysis methods to overcome problems identified during the testing sequence and recommended method applications and needed research.

The results of over 2000 scenarios tested in this project demonstrated the feasibility of direct stability calculation of network models up to 225 generators. The TEF method was shown to be as accurate as the step-by-step method when the same model is used. Computation speed is faster than the time-domain methods for network models smaller than 100 generators. The additional information provided by the TEF method makes it very attractive when relative stability of different plans must be compared or when stability limits must be calculated very quickly, as is the case in power system operations.

These results prove that direct stability analysis is possible in realistic power system analysis and that many important applications exist. Several improvements were intentionally excluded from this research but are critically needed before the TEF can be considered a complete complement to time-domain methods. Computation speed and efficiency have to be improved; models for exciters, load, and other components that affect power system response during and beyond first-swing analysis must be included; and the information provided by the method must be more fully utilized. Some of these improvements are well known, and others will require basic research.

Research is continuing with the objective of demonstrating on-line calculation of transient stability limits by 1991. Software developed in the research is available from EPRI's Electric Power Software Center (code name DIRECT). A final report on the project was published in late 1986. *Project Manager: J. V. Mitsche*

R&D Status Report
ENERGY MANAGEMENT AND UTILIZATION DIVISION

Fritz Kalhammer, Vice President

ADVANCED BATTERY FOR ELECTRIC VEHICLES

The introduction of large numbers of on-the-road electric vehicles (EVs) in the United States would result in a more economic use of base-load electric generating capacity, thereby benefiting both utilities and their customers. In close cooperation with DOE and the Electric Vehicle Development Corp., EPRI's Energy Management and Utilization Division is conducting a program to facilitate the development of EVs. One focus of program activity is an advanced, rechargeable lithium battery system, which promises significant improvements in EV range and acceleration capability.

Initially, fleet EVs are the preferred option for commercialization (*EPRI Journal*, July/August 1986, p. 22). Preliminary specifications have been defined for EVs that could meet utility and other fleet mission requirements. In addition to the benefits afforded the utility supplying the electric power, battery propulsion is expected to offer the vehicle owner reduced operating costs.

There are more than 2.5 million gasoline-type fleet vans in use in the United States, and the duty cycle of many is such that they could be replaced by electric vans with today's commercially available battery technology. Despite many years of focused effort in battery development, however, and the achievement of major advances in several related technologies, no currently available battery system can meet all fleet vehicle performance, cost, and life requirements.

The lead-acid battery, still the only commercially available on-the-road battery system, suffers from a limited energy storage capability, which restricts the achievable range between battery recharges. In a variety of urban driving cycles, a practical range of 55–65 miles (89–105 km) has been measured for commercially available Griffon vans with a conventional lead-acid battery system. Although this range is adequate for many delivery-type applications, it limits the flexibility of the vehicle's operating schedule. (General Motors Corp.'s Griffon was evaluated at the Tennessee Valley Authority's Electric Vehicle Test Facility in Chattanooga and is included in the fleet being used by TVA and EPRI for testing advanced batteries and drive systems.)

Lithium–metal sulfide battery

The battery system remains a key limitation to a more extensive introduction of fleet EVs, but a number of more advanced batteries now emerging promise to significantly improve vehicle range. The development of one such system, the lithium–metal sulfide battery, is currently being sponsored by EPRI, with support from DOE. EPRI's prime industrial contractor is Gould, Inc. (RP2415-1); additional work is being performed by the Argonne National Laboratory. The two contractors have extensive experience with this technology: it was first developed at ANL in the early 1970s and has been under continued development at Gould since 1976.

A lithium–metal sulfide battery of the same weight or volume as the lead-acid battery it would replace should more than double an electric van's practical driving range and significantly increase its acceleration performance, according to goals established for the new battery system. These goals, which are expected to be demonstrated by 1987, are as follows.

- High energy density (Wh/L): 3 times that of the lead-acid battery
- High specific energy (Wh/kg): 2.5 times that of the lead-acid battery
- Safe operation and storage: free from explosions, thermal runaway, and gas releases
- High reliability: insensitive to mechnical and thermal shock, capable of repeated freezing and thawing, safe in terms of voltage reversal and overcharge, predictable failure modes
- Cycle life of 500 cycles at 100% depth of discharge and 1200 cycles at 80% depth of discharge
- Insensitive to the environment
- High rate capability: 1-hour discharge and 1-hour recharge
- Totally sealed and maintenance free
- Cost comparable to that of the lead-acid battery

The lithium–metal sulfide battery features a molten salt electrolyte instead of the aqueous electrolyte (acid or alkali) more commonly used in batteries. A molten salt electrolyte permits the use of far more energetic electrode materials, resulting in increased battery storage capability per unit weight and thus increased EV range. Also, because of their very high ionic conductivity, molten salts enable high-power operation, which would improve EV acceleration and hill-climbing capability.

Lithium, a very electrochemically active metal, is used for the negative electrodes. Because elemental lithium would be liquid at the battery's operating temperature of 450°C, the lithium is alloyed with aluminum. This allows the negative electrode material to be fabricated into plates that remain stable, solid components during extended battery operation. Iron sulfide is used for the battery's positive electrodes. Both negative and positive electrodes are easily fabricated by the cold compaction of powdered materials—hence the low manufacturing cost of the battery system.

The separators between the electrodes consist of powdered magnesium oxide, one of the few ceramic materials that can withstand the highly reducing conditions present at the negative electrode–electrolyte interface. The magnesium oxide is mixed with the electrolyte powder and then cold-compacted to form rigid separator layers.

The design of the lithium–metal sulfide cell is quite similar to that used in a conventional lead-acid battery: it features a parallel array of plates in a prismatic configuration (Figure 1). The other major cell components are a thin steel case, an electrode particle retainer system, and a specially designed cell seal.

A series array of such cells will make up a full-size battery system. Except for the use of air coolant lines, the battery is a totally sealed system during operation. Its high operating temperature relative to that of aqueous electrolyte batteries requires the addition of a high-performance, thermally insulating containment vessel. Such vessels have been fabricated and tested and have shown no special problems in manufacture, cost, or operation.

With a containment vessel of this type, a battery would be able to maintain its operating temperature for several days without an external power supply. If the battery is allowed to cool to room temperature (for routine maintenance and repair, for example), no problems would be likely to result from the freezing of the electrolyte within the cells. Indeed, extensive testing of cells through freeze-thaw cycling has not caused a single cell failure to date.

Although the high operating temperature adds a measure of complexity to the battery design, it also has a beneficial aspect in that waste heat (always formed in a battery during use) can easily be rejected. In the case of aqueous batteries, overheating can severely impair performance, and many problems have been experienced in operating such conventional ambient-temperature batteries during the summer.

It should be noted that the lithium–metal sulfide battery is quite safe during operation and storage. In addition, it requires no provisions for pumps, watering, or special ventilation equipment.

Directions for R&D

The EPRI contracts with Gould and ANL call for the fabrication and testing of battery submodules in early 1987. The tests will be carried out at ANL's National Battery Test Facility and at TVA's Electric Vehicle Test Facility. TVA is helping to fund these first operational submodules. The next major step will be the construction and testing of a full-size battery system. Table 1 shows its projected performance characteristics. Present plans call for the new battery to provide essentially the same voltage as the lead-acid battery it will replace; thus, both vehicle range and performance will be improved. The first full-size lithium–metal sulfide battery is to be fabricated by mid 1988. It will then be delivered to TVA for on-the-road testing.

In a related effort, a commercialization plan will be defined to identify a battery manufacturer, select the first customer use area, and provide financial support to promote product sales. Meanwhile, Gould will continue work to demonstrate increased battery life and reduce the costs of materials and manufacturing.

Table 1
PROJECTED CHARACTERISTICS OF LITHIUM–METAL SULFIDE BATTERY

Weight	504 kg (1109 lb)
Volume	442 L (15.6 ft^3)
Voltage (162 cells, average discharge)	216 V
Energy output (under SAE driving cycle J227a/D)	36 kWh
Power at 80% depth of discharge (30 s)	45 kW
Specific energy	72 Wh/kg
Specific power	89 W/kg
Power/energy ratio	1.24

In addition to its planned use in on-the-road vehicles, the battery can be configured to provide especially high power levels, a feature that has attracted Department of Defense interest. Gould is therefore currently developing the battery for military as well as nonmilitary applications, including submarine power, emergency power, and pulsed power for electromagnetic guns.

At the same time the system is receiving increased attention at Gould, ANL is making major advances that could further improve battery performance. For example, recent results have shown that modifying the electrolyte composition makes it possible to use iron disulfide for the positive electrode without the gradual capacity decline previously experienced with this material during cycling. The implication of this finding is that significant improvements in both specific energy and specific power may be feasible in a long-lived, practical battery—improvements that would result in even better vehicle range and performance.

Because of its attractive features and relatively simple construction requirements, the lithium–metal sulfide system promises to make a rapid transition from its present engineering development status to small-scale production. Early technical and marketing data indicate that the planned battery performance goals will be met, paving the way for successful commercialization. It is anticipated that commercialization will in turn help utilities achieve a more economic use of baseload electric generating capacity, initially through the introduction of electric fleet vehicles and later, if the marketplace permits, through the far broader use of electric passenger vehicles.
Project Manager: Robert D. Weaver

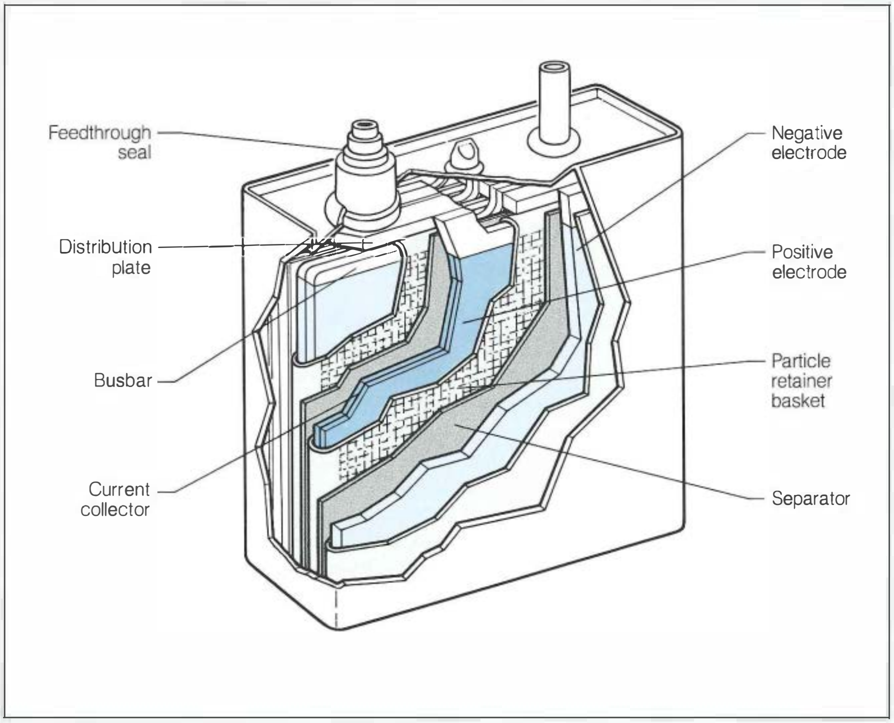


Figure 1 The multiplate lithium–metal sulfide battery cell shown here is similar in design to a conventional lead-acid cell. This new battery technology, being developed with EPRI support, promises to improve the range and performance of electric vehicles.

R&D Status Report
ENVIRONMENT DIVISION

Stephen C. Peck, Acting Director

HEALTH RISK ASSESSMENT FOR WATERBORNE TOXIC EMISSIONS

The electric power industry is subject to a variety of federal and state regulations designed to control the discharge of toxic pollutants. For example, the Clean Water Act of 1977 specifies 65 pollutants or groups of pollutants whose discharge into surface water is regulated by EPA. In the long run, toxic emissions regulation will have to take into consideration the health risks of emissions. Assessing health risks is a complex task, however, and industry and government agencies have emphasized the need for methodologies that can be used to calculate chronic health risks associated with alternative levels of regulation. EPRI's Environment Division is developing such methodological tools to help utilities investigate potential emission problems associated with planned or existing facilities.

Toxic substances can be emitted by many different types of industrial facilities, including coal-fired plants. Discharges from coal-fired plants are receiving special attention because the use of coal for power generation is expected to increase. Under RP1826 EPRI has developed a computer program, WTRISK (water risk), that tracks emissions from a coal-fired source through the environment to determine the degree of exposure and consequent health risk to a regional population. The forerunner of WTRISK was designed to cover the emission and transport of pollutants in all environmental media, and WTRISK retains this capability; however, subsequent model development and applications have focused on waterborne emissions.

The WTRISK approach is easily adapted to many types of situations—for example, the following.

- Preparing environmental impact reports
- Assessing potential health risks in response to regulatory licensing processes
- Investigating the health impacts of alternative regulatory requirements
- Responding to public concern about potential emissions
- Comparing the risks and costs of alternative approaches to controlling toxic emissions
- Improving long-term planning

Although WTRISK was developed for utilities to apply to coal-fired power plants, the methodology could be used for toxic emissions from most point sources, provided the emissions are reasonably continuous.

Model capabilities

The WTRISK program is composed of four modules: emissions, transport, exposure, and risk. As a result of this modular structure, WTRISK is very flexible; it is easily modified and readily accommodates alternative models in these four areas.

The emissions module uses information on fuel characteristics and on plant operating conditions—along with direct measurements, if available—to estimate the rate of release of a substance to the environment. The substance may be released into the atmosphere with gas and ash, directly discharged into surface waterways, or discharged into groundwater through leaching and runoff. The module's estimates of emission concentrations are passed to the transport module.

The transport module calculates the movement of the emitted substance through the atmosphere, waterways, and soil—using appropriate models for each medium—and estimates the concentration in each medium. The module also calculates any chemical changes the substance may undergo during transport to make it more toxic or more inert.

The exposure module uses the environmental concentrations from the transport module to calculate exposure rates for the affected population. The module addresses the three basic pathways by which an emission can enter the human body—inhalation, absorption through the skin, and ingestion. Ingestion may be a direct pathway, as in the drinking of polluted water. Or it may be indirect, as when pollution occurs at the lower end of a food chain and humans subsequently consume the affected plants, livestock, or fish; in this case, the pollutant may increase in concentration as it moves up the food chain.

In the risk module, exposure rates are combined with regional population data and dose-response models to calculate the change in the incidence of chronic health effects in the affected population. WTRISK contains six alternative dose-response functions. Parameters for the dose-response functions may be estimated or obtained from the literature. For health effects that have thresholds or that cannot, for other reasons, be determined by using dose-response models, health risks must be calculated separately on the basis of results from the exposure analysis.

The calculation of chronic health risks requires various types of input, several of which will have significant uncertainty. WTRISK helps the user investigate the sources and propagation of uncertainty through the calculations. In addition to applying conventional techniques to study how risk estimates vary with model parameters, the user can observe how different models may change the results at various stages of the analysis.

Case study

After its initial development, WTRISK was used in a case study to analyze the health risks associated with selenium emissions at a coal-fired power plant in the eastern United States. The selenium was being discharged into a small creek that is a tributary of a major river used for fishing and as a source of drinking water.

The analysis was separated into two parts. The first consisted of surface water transport calculations to determine how emissions from the power plant affected selenium concentrations in the river. The primary sources of human exposure were determined to be fish and drinking water. The second part of the analysis estimated the increased consumption of selenium and the consequent increase in selenium-related health effects due to the emissions.

The study found that even in the worst scenarios (e.g., ones using the lowest recorded river flow rates), the incremental selenium exposure from plant emissions was small. Except for the most adverse scenarios, concentrations remained well below the health-based threshold established by EPA.

The available data on selenium are not sufficient for calculating specific health effects associated with various levels of the element. By using the EPA-established threshold, however, the mean exposure rate was translated into an expected number of people who might exceed the threshold and therefore be at risk of developing selenosis, a condition associated with toxic levels of selenium. The results of the study showed that the health effects attributable to plant selenium emissions under reasonable conditions are negligible.

The next step in the project is to adapt WTRISK to a wider range of utility problems. Important topics include surface water conditions at coal tar sites and groundwater contamination. A report on the WTRISK methodology is forthcoming. The code is scheduled to be released by the Electric Power Software Center by December 1987. *Project Manager: Anthony D. Thrall*

RADIATION STUDIES PROGRAM

Although the biologic and health effects of ionizing radiation have been studied extensively, most of the research has involved high levels of exposure. To ensure an adequate measure of safety, standards for low-level (i.e., occupational) exposures are based on conservative assumptions and on extrapolation from high-level exposures. Despite the conservative standards for protection, there is a persisting public perception that exposure to low-level radiation entails unusual risks to health—a perception that can lead to regulatory delay and unnecessary litigation. This report describes a small new EPRI research effort that is exploring the issues of radiation risk perception, communication, and assessment.

Until recently, EPRI had not conducted research in the area of radiation health effects. The impetus for the new program came from some of the Institute's industry advisers, who expressed interest both in research to reduce uncertainty in the existing risk estimates for low-level radiation exposure and in research to provide ways of improving the public's understanding of those estimates. As a result, an ad-hoc committee representing the Nuclear Power Divisional Committee and the Environment Divisional Committee was formed. This group encouraged EPRI staff members to pursue further planning, which culminated in four workshops held in April 1986 in Palo Alto, Atlanta, Washington, and Chicago. Representatives of 24 nuclear utilities attended, and a large majority endorsed an EPRI research program in radiation studies. In addition, the attendees established priorities among the several research areas discussed.

The issues of radiation risk perception and communication were seen as being of the highest priority. It is now generally recognized that the public perception of risks differs considerably from that of technical experts. Some of the reasons for this difference are understood. For example, the degree of personal control strongly influences the risk that people are willing to accept. If a risk is considered voluntary, its perceived acceptability rises substantially. We also know that interest by the news media in certain kinds of risk focuses public attention and can lead to an exaggerated perception of those sources of risk. Still, there is much we do not know about how people perceive and evaluate risks.

The utility representatives also expressed concern about the related issue of risk communication and recommended it for research attention. This concern reflects the sense of frustration felt by many radiation scientists over their inability to adequately communicate technical facts about risk. Members of the public feel equally frustrated with the incomprehensible answers they get to questions about risk. We do not know enough about meaningful measures with which the public can assess technologic risks. We also do not know how the perception of these risks is influenced by the medium through which information is presented. Nor do we know enough about the characteristics that create credibility for the communicator of risk information. As we saw at Chernobyl, the simple presentation of facts is often ineffective.

Further, we do not know enough about how people make decisions regarding the acceptability of a technology, whether that technology be a nuclear reactor, a transmission line, or a transformer containing polychlorinated biphenyls. Clearly, more than an accurate assessment of risk is necessary; most people are equally interested in benefits. They also want to know about alternatives to the proposed technology. In short, the perception and evaluation of technologic risks and benefits by the public are new areas of research that have not received adequate attention at EPRI or elsewhere. Over the next year, EPRI staff will be determining the most useful ways to explore these issues.

The workshop attendees also showed strong support for the planning of an epidemiologic study of workers in the nuclear power industry. Although extensive epidemiologic studies have been conducted on populations exposed to radiation, there has been no large-scale study of the effects, if any, of radiation exposure on the health of workers in the U.S. nuclear power industry.

There are two reasons for conducting such a study. One is to provide direct evidence on the risk to this population. No increase in cancer or other diseases among nuclear plant workers is expected; however, this expectation is largely based on risk estimates derived from studies on populations with very different characteristics and radiation exposure conditions—the survivors of the atomic bombings of Japan. In the case of the bomb victims, radiation exposures were almost instantaneous. In the case of workers, exposures are at very low dose rates and persist over many years. Moreover, there are biologic, behavioral, and occupational factors that may affect the risk estimates for plant workers. A second, closely related reason for undertaking such a study is that the information derived can help provide a scientific basis for responding to any future litigation. Commonwealth Edison Co. has already begun a study of plant workers, which is likely to provide useful guidance as planning for a larger, industrywide study progresses.

Other areas of research discussed at the workshops but assigned a lower priority were radiation biology (in particular, stimulatory effects), indoor radon exposure, and the concept of probability of causation.

The Radiation Studies Program has now been established in EPRI's Environment Division. In coordination with the Nuclear Power Division, the new program will address the issues discussed above. It will also assume responsibility for existing research on nonionizing radiation, which focuses on electromagnetic fields. *Program Manager: Leonard Sagan; Project Manager: Joel Cehn; Nuclear Power Division Coordinator: C. J. Wood*

R&D Status Report
NUCLEAR POWER DIVISION

John J. Taylor, Vice President

ARMP-02 CORE PHYSICS ANALYSIS PACKAGE

A major objective of the reactor performance subprogram has been to develop analytic tools that utility engineers can use to model reactor cores under steady-state or quasi-steady-state operating conditions. Utilities need such analytic capabilities to support plant operations, recognize any departures from predicted plant behavior, and evaluate the expected performance of future core reload designs. To satisfy this objective, EPRI developed a system of interrelated computer programs, the advanced recycle methodology package (ARMP), which was first released in 1977. This package has enabled utilities to perform their own analyses without having to depend on codes or procedures supplied by fuel vendors. Since the release of the original ARMP, a considerable amount of additional research and development has made the series more flexible, more accurate, and easier to use. The results of this effort have been incorporated into a secondgeneration computer code package, ARMP-02, to be released for production use by the Electric Power Software Center (EPSC) in early 1987.

The ARMP-02 code package consists of a series of separate computer programs that can perform several general functions.

▫ Lattice physics codes, which determine the properties (effective cross sections) of fuel assemblies under a wide range of expected operating conditions, such as fuel exposure, temperature, moderator temperature, void level, soluble boron concentration, and control rod presence

▫ Data parameterization codes, which reduce the assembly cross sections calculated by the lattice physics codes into a parametric form appropriate for use in coarse-mesh (nodal) core simulators

▫ Three-dimensional nodal core simulator codes, which predict the behavior of a reactor core under various operating conditions

▫ Fine-mesh diffusion theory code, which details a pin-by-pin representation of the core depletion in two dimensions and can also be used for normalization of the three-dimensional PWR core simulator model

ARMP-02 supports two separate calculation paths, depending on whether the user is modeling a PWR or a BWR. Table 1 shows the individual component codes for the PWR and BWR paths. Figure 1 shows the flow of information among the codes within each path.

In addition to the individual codes, the ARMP-02 package consists of extensive documentation (which includes code manuals), system benchmarking experience, and recommended procedures for LWR analysis.

PWR analysis path

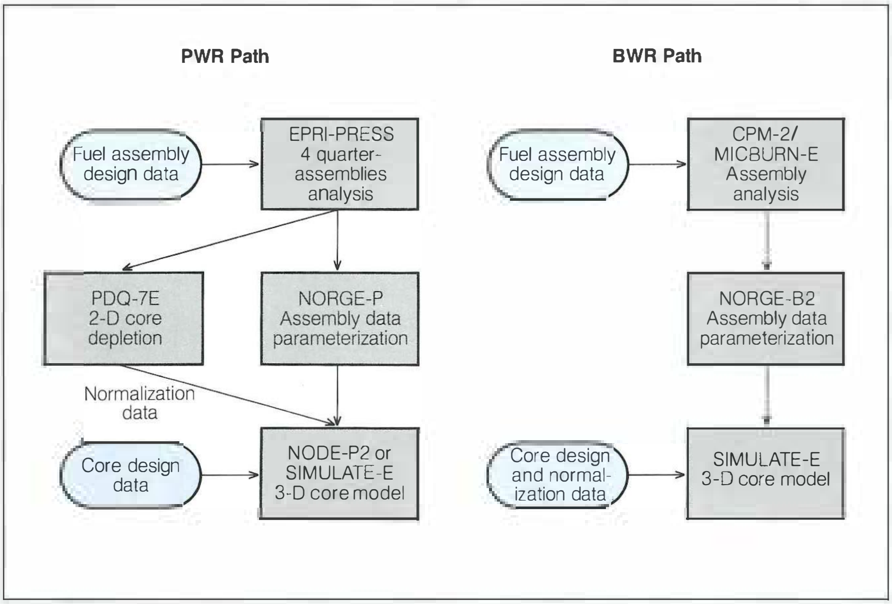
The first step in the PWR analysis path is to develop a data base of fuel assembly properties for each type of fuel in the reactor. (A fuel type is characterized by its initial enrichment and burnable poison content, which is typically referred to as its color. The data base consists of effective two-group cross sections and integral properties, such as infinite multiplication factors and migration areas. In ARMP-02 this data base is developed by using either the EPRI–PRESS code or its individual components (CELL-2, NUPUNCHER-2, APLB, GAD, and PDQ-7E).

A small section (pin cell) of an assembly is analyzed first with a multienergy group transport representation in a one-dimensional cylindrical geometry with the code CELL-2. The broad-group cross sections thus produced constitute the input to two-dimensional fine-mesh diffusion theory calculation of the assembly geometry in two energy groups by using the PDQ-7E code. The configuration typically analyzed consists of one-quarter of each of four adjacent assemblies. Because the four quarter assemblies may represent different fuel types or colors, this configuration is referred to as a color set. The NUPUNCHER-2 code processes the CELL-2-generated data into a format appropriate for PDQ-7E. APLB and

Table 1
ARMP-02 COMPONENT CODES

Function Performed	Code: PWR Path	Code: BWR Path
Lattice physics	EPRI–PRESS or its components (CELL-2, NUPUNCHER-2, APLB, GAD, PDQ-7E)	CPM-2 MICBURN–E
Data parameterization	NORGE–P	NORGE–B2
Two-dimensional core depletion	PDQ-7E	...
Three-dimensional core simulator	NODE–P2, SIMULATE–E	SIMULATE–E
Auxiliary codes	BETCY (assembly input shuffling for PDQ-7E)	RODDK (estimate of control rod worth, SIMULATE–E) ABLE (analytic estimate of reflector albedos, SIMULATE–E)

Figure 1 Logical flow diagram, indicating the function of the primary components of the ARMP-02 code system and their input requirements.



GAD are used with CELL-2 and NUPUNCHER-2 to produce diffusion theory parameters for burnable poison pins and gadolinium-loaded fuel if they are present in the assembly.

In addition to its use for the color-set calculations, PDQ-7E is also used in a stand-alone mode for two-dimensional analyses of the entire core on a pin-by-pin basis. Because of symmetries, typically only a quarter or an eighth of the core need be modeled. This two-dimensional depletion calculation is needed for beginning-of-cycle normalization data for the three-dimensional coarse-mesh nodal core simulator codes, as well as for the determination of pin flux peaking factors used for in-core fuel management.

The assembly data generated in the color-set calculations are parameterized by the NORGE–P code, using (as independent variables) a set of parameters to which the data have been found to be most sensitive. The parameterized data base, as well as information about the configuration of the core, constitutes the basic input for the nodal core simulator codes NODE–P2 or SIMULATE–E. These codes use a coarse geometric representation (typically 1–4 nodes per assembly in the radial direction, 12–24 nodes or more in the axial direction) to represent a reactor in full three dimensions.

BWR analysis path

The assembly data base for the BWR path is generated by using the lattice physics codes CPM-2 and MICBURN–E. CPM-2 carries out one-dimensional multigroup calculations for the different types of fuel pins, water holes, structural components, and control rods present in a BWR assembly. This calculation is followed by an analysis of the assembly geometry in two dimensions but with fewer broad energy groups (typically consisting of 12). Both calculations are carried out in the same CPM-2 run using a collision probability (integral transport) approach.

The MICBURN–E code is a one-dimensional multienergy transport code similar to CELL-2. It represents the complex depletion behavior (the onion-skin effect) of gadolinium poison that is incorporated into some of the fuel pins to reduce flux peaking and control reactivity. The burnup-dependent average properties of such gadolinium-loaded pins, as calculated by MICBURN–E, constitute an input to CPM-2 for assembly analysis. The parameterization of the CPM-2–generated assembly data is done with NORGE–B2, which is the BWR analog of the NORGE–P code. SIMULATE–E represents the full core in three dimensions by using a nodal approach.

The new package

The ARMP-02 code package represents a significant enhancement over the previously released ARMP core physics analysis capability. The primary enhancements are in ease of use, flexibility, and accuracy. Although the PWR lattice physics procedure in ARMP-02 is based on the same general approach (color-set methodology) as is the original ARMP, most of the user effort necessary for running the different pin-cell calculations, for preparing the effective diffusion theory constants needed for representing burnable absorbers in PDQ-7E, and for the disk file management burden have been taken over by the control module of EPRI–PRESS. This improvement has significantly reduced the effort required for the production of assembly data.

Whether used alone or as a module in EPRI–PRESS, the CELL-2 code contains many enhancements and options not present in the ARMP code EPRI–CELL from which it was derived. The most significant of these is an option to use cross-section libraries derived from the state-of-the-art national nuclear data file ENDF/B–V. Calculations based on this library agree more with reactor measurements of critical soluble boron concentrations, control rod worths, and other characteristics than do predictions based on the earlier production libraries.

Similarly, the BWR lattice physics code CPM-2 is an upgraded version of the EPRI–CPM code, which played an auxiliary role in the original ARMP package. Although the analytic approach in CPM-2 is the same as that in ERPI–CPM, the user effort needed to prepare input for a typical assembly calculation is reduced by at least a factor of four. The data parameterization codes, NORGE–P and NORGE–B2, are a one-step replacement for the ARMP procedure implicit in codes EPRI–FIT and SUPERLINK, which had to be run sequentially. The new codes are geared toward a more complete parameterization of the assembly data.

NODE–P2 was developed by completely reprogramming the ARMP code NODE–P. The new code is considerably faster and less susceptible to convergence-related problems. The advanced nodal simulator SIMULATE–E has been developed since the release of the original ARMP. SIMULATE–E is a very flexible core analysis code that can represent all significant local feedback effects for both BWRs and PWRs, including control rod insertion, moderator voiding, moderator density variation, fuel depletion, fuel temperature, and xenon and samarium transients.

In addition to the above primary components, ARMP-02 contains a few auxiliary codes developed to facilitate various common LWR analysis tasks. The first of these, BETCY, is used to modify the input data for a PDQ-7E pin-by-pin core calculation in a manner that would correspond to the movement, replacement, or relocation of assemblies within a core. This capability is used to facilitate iterative PDQ calculations aimed at determining the optimal location for fuel assemblies for a reload core. RODDK and ABLE are auxiliaries for SIMULATE–E. The first can quickly estimate control rod worths to help locate the most reactive rods, using an approximate approach. The latter generates analytic estimates of the reflector albedos for use as boundary conditions in SIMULATE–E.

A number of utilities have been using different prerelease ARMP-02 components. The final package will contain corrections and enhancements resulting from the prerelease testing.

ARMP-02 is part of the reactor analysis support package (RASP). The ARMP-02 package can be interfaced by RASP links with system transient and thermal-hydraulic codes, such as RETRAN and VIPRE, and eventually with the three-dimensional transient neutronics code ARROTTA to provide the core physics input for safety analysis and licensing calculations. *Project Managers: Odelli Ozer and Walter Eich*

IMPROVED HIGH-STRENGTH ALLOYS FOR LWR APPLICATIONS

Nickel-base superalloys, such as alloy X-750 and alloy 718, are widely used in light water reactors (LWRs) for bolts, springs, guide pins, and other structural hardware where high strengths are required. In recent years, however, some stress corrosion failures have occurred in reactor components made of these alloys. As a result, EPRI initiated a research project to determine if the stress corrosion cracking (SCC) resistance of alloys X-750 and 718 could be improved by modifying their heat treatments (RP2181). Because the currently used heat treatments for these alloys were designed for service in high-temperature gas environments, it was reasoned that the treatment could be changed to provide better performance under the very different operating conditions found in boiling water reactors (BWRs) and pressurized water reactors (PWRs).

Although alloys X-750 and 718 are both being studied as part of this project, the initial emphasis was on alloy X-750 because it is used more extensively than alloy 718, and a greater number of failures in alloy X-750 components have been reported. A two-step approach is being taken: laboratory testing is used to identify heat treatments that improve the SCC behavior under laboratory conditions; then in-plant testing of several heats of material to verify that the new heat treatments confer performance benefits under the service conditions of interest, which include the reactor core. The second step is essential because it is not possible to duplicate exactly the environmental conditions (e.g., water chemistry and radiation levels) of the reactor core in the laboratory

The heat treatment used for many of the alloy X-750 components now in service in the field consists of a relatively low-temperature (1800°F [982°C]) solution anneal, then a 24-h stress-equalization step at 1625°F (885°C), and finally an aging treatment at 1300°F (704°C) for 20 h. This heat treatment is called the AH treatment by the industry. Preliminary laboratory studies showed that two other heat treatments,

Figure 2 The SCC susceptibility of alloy X-750 in different heat treatment conditions exposed to a simulated 360°C PWR primary environment. The AH heat treatment is currently being used for many high-strength components found in the field. A low run-out stress intensity indicates SCC-susceptible material.

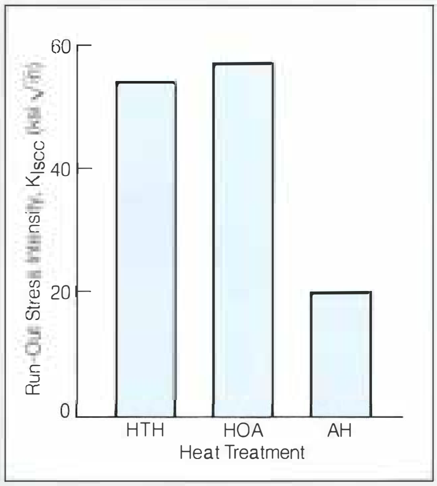
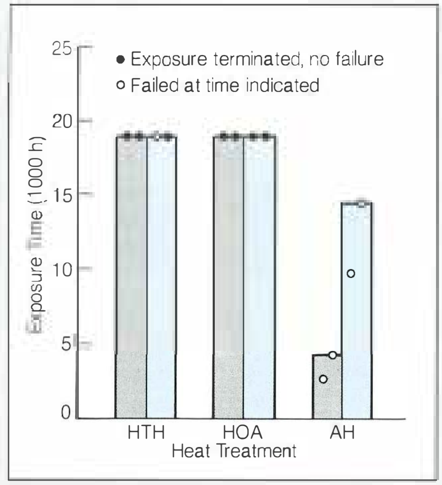


Figure 3 Time to failure for several heat treatments of alloy X-750 exposed to simulated BWR (color) and PWR (gray) primary water. Both HTH and HOA offer a significant improvement in SCC resistance. Material given the HTH treatment has approximately a 10% greater yield strength, thus making it more attractive from a design standpoint.



in particular, appeared to impart improved SCC resistance to alloy X-750. Unlike the AH treatment, both of these heat treatments used only a two-step thermal treatment: a high-temperature anneal at 2025°F (1107°C) for 1 h followed by an aging treatment at either 1300°F (704°C) for 20 h (HTH treatment) or at 1400°F (760°C) for 100 h (HOA treatment).

In the laboratory phase of the test program the SCC behaviors of AH-, HTH-, and HOA-treated specimens of alloy X-750 were compared. The reactor environments and loading conditions were duplicated as closely as possible, except that no radiation field was present (Figure 2). The test specimens were initially fatigue-precracked to ensure that a crack was present, loaded to a stress intensity of 60 ksi $\sqrt{\text{in}}$ (66 MPa $\sqrt{\text{m}}$), and then placed in the test environment (simulated 680°F [360°C] PWR primary water). After 6000 h of exposure, only slight crack growth took place in the HTH- and HOA-treated specimens, whereas the crack in the AH-treated material grew to a point at which the stress intensity was reduced to one-third its original value. The greater the value of this so-called run-out stress intensity, the greater the load a component can sustain.

Crack propagation resistance, however, is only one of the corrosion-related properties of a material that are of interest to the designer of reactor components. For example, the crack initiation behavior is of equal if not greater importance because more than 90% of the life of a component is generally spent in the initiation phase. Constant-deflection bend tests were carried out in simulated BWR and PWR primary water. Alloy X-750 specimens given the AH, HTH, and HOA heat treatments were exposed for times up to 19,000 h; the specimens were examined at 3000- to 5000-h intervals. The results clearly show that the crack-initiation resistance of the HOA and HTH heat-treated materials is better than that of the AH heat-treated material (Figure 3).

From these results it is clear that alloy X-750 heat-treated to either the HTH or HOA condition offers a far greater resistance to SCC than if heat-treated to AH. In both initiation and propagation tests, the HOA treatment appeared to be slightly better than the HTH treatment. However, the yield strength of the material must also be considered, and the yield strength of the HTH-treated material is about 15% greater than that resulting from the HOA treatment (105 ksi [724 MPa] versus 92 ksi [634 MPa]). For this reason the in-reactor testing portion of this research project is emphasizing testing the HTH heat treatment.

In-reactor verification tests are in progress in both BWR and PWR cores. Specimens from two heats of alloy X-750 given the HTH heat treatment will be tested for two fuel cycles in a high-radiation portion of the core. Stress is applied to the specimens by using the swelling characteristics of B_4C and Al_2O_3 in a radiation field. Mixtures of these two substances are packed inside a cylindrical test specimen, thus causing a gradually increasing stress to be applied during irradiation. The results of these tests will not be known until this summer. Future laboratory and in-reactor testing will also be directed toward the improvement of alloy 718 and other promising high-strength alloys. *Project Manager: J. Lawrence Nelson*

New Contracts

Project	Funding/ Duration	Contractor/EPRI Project Manager
Advanced Power Systems		
Solid Oxide Fuel Cell Test (RP1041-23)	$100,000 6 months	Tennessee Valley Authority/*R. Goldstein*
Guide for Preliminary Economic Evaluation of Potential Pumped-Hydro Sites (RP1745-30)	$317,600 15 months	Harza Engineering Co./ *C. Sullivan*
Project Coordination for Diagnostic Instrumentation (RP2102-21)	$72,000 4 months	Barras & Associates/ *L. Angello*
Thermodynamic Analysis of Repowered Steam Systems (RP2565-14)	$104,700 15 months	S. Levy, Inc./*A. Cohn*
Study of Phased Construction for Shell Gasification in Combined Cycles (RP2699-8)	$411,900 24 months	Fluor Technology, Inc./ *M. Gluckman*
IGCC Site-Specific Plant Studies (RP2773-7)	$325,000 17 months	Florida Power & Light Co./ *J. Fortune*
Coal Combustion Systems		
Boiler R&D for Advanced Fossil Fuel Power Plants (RP1403-14)	$2,373,000 40 months	Combustion Engineering, Inc./*G. Touchton*
Fossil Fuel Plant Retrofits for Improved Heat Rate and Availability (RP1403-16)	$54,500 6 months	Gilbert/Commonwealth, Inc./*G. Touchton*
Delaware Highway Ash Utilization Demonstration (RP2422-3)	$249,700 36 months	Delmarva Power & Light Co./*D. Golden*
Site Support for TVA 160-MW (e) AFBC Demonstration (RP2543-8)	$227,500 23 months	Combustion Systems, Inc./ *T. Boyd*
Emission Reduction Analysis Model: Maintenance and Enhancements (RP2575-7)	$331,000 22 months	Putnam, Hayes & Bartlett, Inc./*M. Miller*
Electrical Systems		
Substation Robotics (RP1497-3)	$80,000 7 months	Southwest Research Institute/*J. Dunlap*
Fundamental Research on Metal Oxide Varistor Technology (RP2667-2)	$1,174,500 36 months	General Electric Co./ *H. Mehta*
Aging of Extruded-Dielectric Power Cables (RP2713-1)	$128,200 12 months	Institut de Recherche de l'Hydro-Québec/ *B. Bernstein*
Perfluorocarbon Tracer Gases for Leak Location in High-Pressure Oil-Filled Systems: Electrical Compatibility Tests (RP7905-2)	$77,300 6 months	Cablec Corp./*F. Garcia*
Energy Management and Utilization		
Field Evaluation of Water-Loop Heat Pump (RP2480-1)	$485,000 40 months	Friedrich Climate Master, Inc./*M. Blatt*
Nonintrusive Appliance-Load-Monitoring Field-Grade Hardware: Development and Field Validation (RP2568-9)	$308,500 17 months	American Science and Engineering, Inc./ *L. Carmichael*

Project	Funding/ Duration	Contractor/EPRI Project Manager
Data and Methodology for End-Use Analysis in the Commercial Sector (RP2788-6)	$185,800 14 months	Decision Focus, Inc./ *T. Yau*
Power Electronics Applications Center (RP2825-1)	$3,000,000 37 months	Tennessee Center for Research and Development/ *R. Ferraro*
Evaluation of Highly Dispersed Platinum Catalysts for Fuel Cells (RP8002-10)	$47,700 9 months	Case Western Reserve University/*R. Goldstein*
Environment		
Ion Identification in the Field and the Laboratory (RP1774-3)	$213,300 18 months	Georgia Tech Research Corp./*R. Patterson*
Methylmercury Analyses in Surface Waters (RP2020-4)	$49,700 10 months	Swedish Environmental Research Institute/ *D. Porcella*
Lake Acidification Mitigation (RP2337-3)	$75,000 5 months	Cornell University/ *D. Porcella*
Nuclear Power		
Radiation Detection and Analysis (RP1399-5)	$30,000 10 months	Pennsylvania State University/*R. Breen*
Condensate Polishing With Powdered Sulfur-Free Ion Exchange Resins (RP1571-9)	$62,800 10 months	Graver Water/*T. Passell*
Theoretical Modeling of Crack Chemistry (RP2006-16)	$33,000 11 months	Massachusetts Institute of Technology/*J. Gilman*
Guidelines for Fuel Reliability Improvement (RP2229-3)	$229,700 18 months	S. M. Stoller Corp./ *D. Franklin*
LMFBR Technical Integration Studies (RP2658-20)	$172,000 20 months	Rockwell International Corp./*E. Rodwell*
Evaluation of the Consequences of Containment Bypass Sequences in BWRs (RP2726-2)	$352,300 21 months	Fauske & Associates, Inc./ *E. Fuller*
Evaluation of the Consequences of Containment Bypass Sequences in PWRs (RP2726-3)	$222,800 17 months	Stone & Webster Engineering Corp./*E. Fuller*
Antivibration Bar Clearance Test and Monte Carlo Program Development (RP2765-2)	$285,400 17 months	Westinghouse Electric Corp./*D. Steininger*
Clotaire Program (RP2810-1)	$600,000 42 months	Commissariat à l'Energie Atomique/*S. Kalra*
Chemistry of and Radiolysis in Boiling Reactor Coolant (RP2816-1)	$50,000 6 months	Atomic Energy of Canada Ltd./*T. Passell*
Operator Reliability Experiments and Model Development (RP2847-1)	$1,184,900 31 months	NUS Corp./*D. Worledge*
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Assessment of Downstream Migrant Fish Protection Technologies for Hydroelectric Application
AP-4711 Final Report (RP2694-1); $55
Contractor: Stone & Webster Engineering Corp.
EPRI Project Manager: C. Sullivan

Comparative Flow Measurements: Grand Coulee Pumping-Generating Plant Unit P/G 9
AP-4712 Final Report (RP2038-1); $55
Contractor: U.S. Bureau of Reclamation
EPRI Project Manager: C. Sullivan

Joint Technical Workshop: Amorphous Silicon Alloys for Photovoltaic Power
AP-4821-SR Special Report; $25
EPRI Project Manager: E. DeMeo

Cool Water Coal Gasification Program: Fourth Annual Progress Report
AP-4832 Interim Report (RP1459); $40
Contractors: Cool Water Coal Gasification Program; Bechtel Power Corp.; Radian Corp.
EPRI Project Manager: N. Holt

Combustion of Two-Stage Coal Liquefaction Residues in a Hybrid Boiler
AP-4835 Final Report (RP2697-1); $32.50
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EPRI Project Manager: W. Weber

Phase Equilibria in Coal Conversion Processes
AP-4836 Final Report (RP367-2); $32.50
Contractor: Purdue University
EPRI Project Manager: L. Atherton

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AP-4849 Final Report (RP2469-1); $32.50
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EPRI Project Manager: M. Epstein

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AP-4850 Final Report (RP2147-3); $32.50
Contractor: University of Wyoming
EPRI Project Manager: C. Kulik

Selective Oxidation of Pyrites in Coal
AP-4873 Final Report (RP2655-6); $25
Contractor: Battelle, Columbus Laboratories
EPRI Project Manager: L. Atherton

COAL COMBUSTION SYSTEMS

Fly Ash Design Manual for Road and Site Applications: Slurried Placement
CS-4419 Interim Report (RP2422-2); Vol. 2, $32.50
Contractor: GAI Consultants, Inc.
EPRI Project Manager: D. Golden

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CS-4809 Final Report (RP1895-24); $25
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EPRI Project Managers: F. Wong, G. Poe

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EL-4658-SR Special Report; $40
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EL-4856 Final Report (RP7841-1); $47.50
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EPRI Project Manager: T. Rodenbaugh

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EL/EA-4858 Final Report (RP2028-5, -8, -9); Vol. 1, $25; Vols. 2 and 3 forthcoming
Contractors: Radian Corp.; General Electric Co.; IIT Research Institute
EPRI Project Managers: G. Addis, J. Guertin

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Advanced Commercial Survey Methods (COMSURV): Demonstration of Optimum Sample Design for Nonresponse Bias Control
EM-4519 Final Report (RP1216-9); Vol. 3, $32.50
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EPRI Project Managers: A. Faruqui, J. Wharton

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EPRI Project Manager: D. Hu

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EM-4815-SR Special Report (RP2381-4); $25
EPRI Project Manager: A. Faruqui

ENVIRONMENT

The Integrated Lake-Watershed Acidification Study: Data Base Documentation
EA-3221 Final Report (RP1109-5); Vol. 5, $32.50
Contractor: Tetra Tech, Inc.
EPRI Project Manager: R. Goldstein

Analysis of Alternative Sources of Cooling Water
EA-4732 Final Report (RP1949-1); $47.50
Contractor: Dames & Moore
EPRI Project Manager: E. Altouney

Development of Methods for Analyzing Organics in Fly Ash
EA-4792 Final Report (RP1057-1); $32.50
Contractor: Oak Ridge National Laboratory
EPRI Project Manager: J. Guertin

Utility Planning Model (UPM) Version 2.0: System Documentation and User's Manual
EA-4807M Final Report (RP1819); $25
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EPRI Project Managers: D. Geraghty, L. Rubin

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EA-4819 Final Report (RP2194-2); $47.50
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EPRI Project Manager: S. Kalra

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EPRI Project Manager: J. Gaertner

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NP-4797 Topical Report (RP1757-36, -37; RP2455-5); $77.50
Contractors: Materials Research & Computer Simulation, Inc.; Fracture Control Corp.
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ASK: PCB Economic Risk Management Model
Version 3.0 (IBM PC)
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EPRI Project Manager: V. Niemeyer

COIL: Contaminated Oil Economic Risk Management Model
Version 3.0 (IBM PC)
Contractor: Decision Focus, Inc.
EPRI Project Manager: V. Niemeyer

DSAS: Distribution System Analysis and Simulation
Version 2.0 (IBM, IBM PC); EL-3591
Contractor: University of Texas at Arlington
EPRI Project Manager: H. Songster

DSWORKSTATION: Distribution Workstation
Version 1.0 (IBM PC)
Contractor: Power Computing Co.
EPRI Project Manager: G. Ben-Yaacov

EPAM: Sampling Design for Aquatic Ecological Monitoring
Version 1.0 (IBM PC, VAX); EA-4302
Contractor: University of Washington
EPRI Project Manager: J. Mattice

ESCORE: Steady-State Fuel Performance Code
Version 1.0 (IBM CDC); NP-4492, Vols. 1–3
Contractor: S. Levy, Inc.
EPRI Project Manager: D. Franklin

FORECAST MASTER: Short-Range Forecasting Model
Version 2.0 (IBM PC)
Contractor: Scientific Systems, Inc.
EPRI Project Manager: S. Braithwait

HARMFLO: Harmonic Power Flow Program
Version 3.1 (IBM, PRIME); EL-4366-CCM
Contractor: Purdue University
EPRI Project Manager: J. Mitsche

MYGRT: Migration of Solute in the Subsurface Environment
Version 1.0 (IBM PC); EA-4543-CCM
Contractor: Tetra Tech, Inc.
EPRI Project Manager: D. McIntosh

RETOU: Residential Time-of-Use Response Model
Version 1.0 (IBM PC); EA-2560
Contractor: Christenson Associates, Inc.
EPRI Project Manager: P. Hanser

SOMIP: Soil Parameter Estimation From Field Measurements
Version 2.0 (IBM)
Contractor: Georgia Institute of Technology
EPRI Project Manager: J. Dunlap

STABIN: Transient Stability Program Output Analysis
Version 1.0 (IBM); EL-4192
Contractor: Iowa State University
EPRI Project Manager: J. Mitsche

TLWORKSTATION: Integrated Transmission Line Software
Version 1.0 (IBM PC); EL-4468, EL-4540-CCM
Contractor: Power Computing Co.
EPRI Project Manager: P. Lyons

UFIM: Utility Fuel Inventory Model
Version 2.0 (IBM)
Contractor: Applied Decision Analysis
EPRI Project Manager: S. Chapel

UNIRAM: Power Generating System Availability Assessment Model
Version 1.1 (IBM, IBM PC); AP-3956-CCM
Contractor: Arinc Research Corp.
EPRI Project Manager: J. Weiss

WAM-E: Fault Tree Evaluation Codes
Version 3.0 (CDC, IBM); NP-4460-CCM
Contractor: Science Applications International
EPRI Project Manager: J. Gaertner

WTRISK: Waterborne Toxic Risk Assessment Model
Version 1.0 (IBM, IBM PC)
Contractor: Mindware Corp.
EPRI Project Manager: R. Wyzga

CALENDAR

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

FEBRUARY

19–20
State-of-the-Art Commercial Cool Storage
Denver, Colorado
Contact: Ronald Wendland (415) 855-8958

24–26
Workshop: Control Systems for Fossil Fuel Power Plants
Atlanta, Georgia
Contact: Murthy Divakaruni (415) 855-2409

MARCH

10–11
Seminar: Maintaining Equipment Qualification
Chicago, Illinois
Contact: Robert Kubik (415) 855-8905

10–12
Conference: Incipient Failure Detection for Fossil Fuel Power Plants
Philadelphia, Pennsylvania
Contact: John Scheibel (415) 855-2850

10–12
Symposium: Power Plant Pumps
New Orleans, Louisiana
Contact: Stanley Pace (415) 855-2826

11–12
Seminar: Maintaining Equipment Qualification
Chicago, Illinois
Contact: Robert Kubik (415) 855-8905

12–13
Seminar: Maintaining Equipment Qualification
Boston, Massachusetts
Contact: Robert Kubik (415) 855-8905

23–26
1987 Joint Symposium on Stationary NO_x Control
New Orleans, Louisiana
Contact: David Eskinazi (415) 855-2918

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