Intelligence Captured

ELECTRIC POWER RESEARCH INSTITUTE

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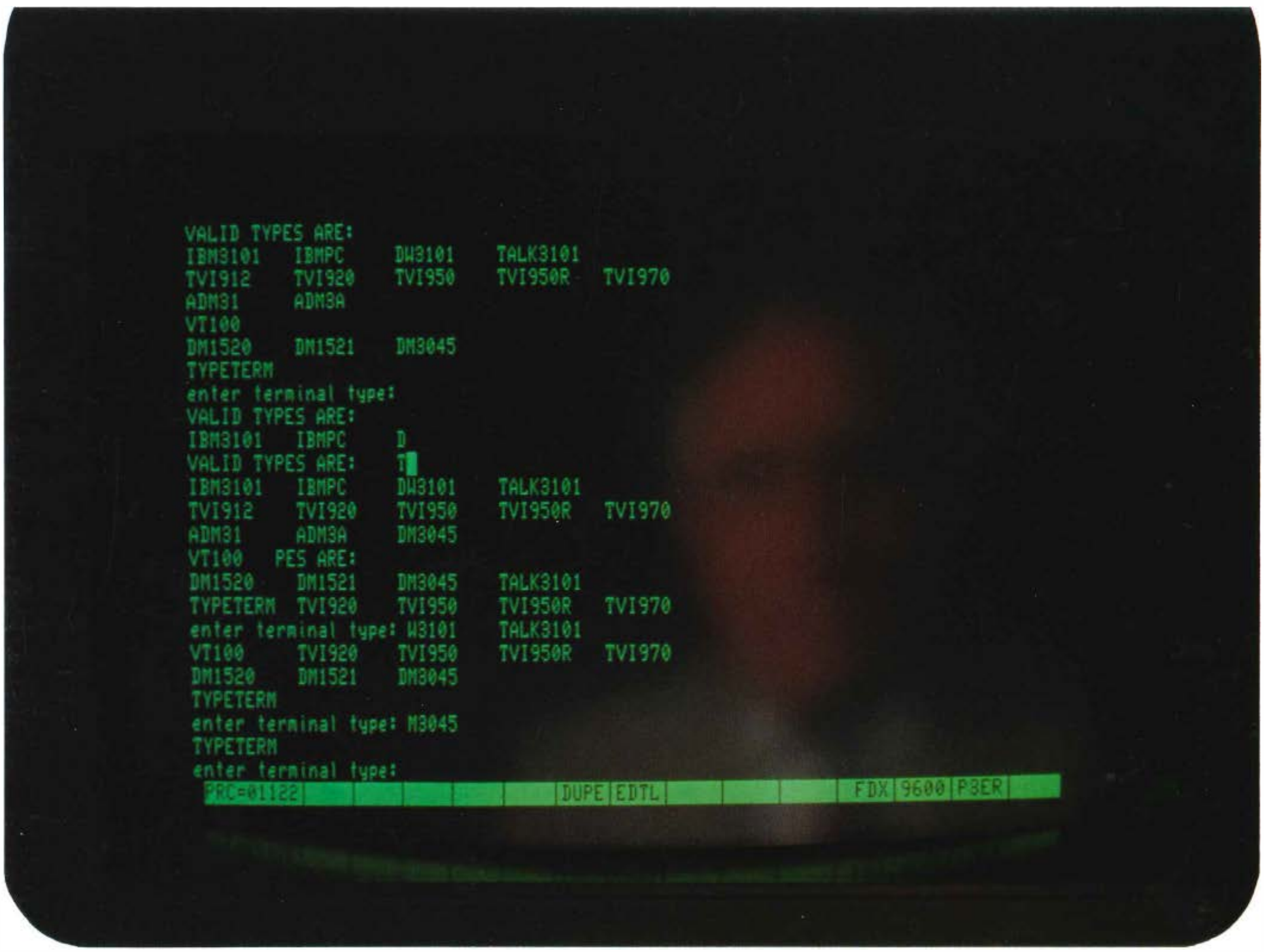

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Cover: Expert systems allow utilities to capture the knowledge and judgment of the seasoned veteran on computer disk and make it widely available to less-experienced personnel when the need for assistance arises.

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Expert Systems for the Utilities' Future

For nearly as long as the computer age is old, researchers have sought to make computing machines faster and smarter: faster through more-efficient circuits and electronic hardware, and smarter through increasingly sophisticated software. An outgrowth of efforts in both areas is the field of artificial intelligence (AI)—a discipline devoted to incorporating logic and reasoning in computers. After more than 20 years' research in AI by the military, universities, and industrial laboratories, we are now seeing the fruits of some of this work. Many innovations found in today's personal computers grew from AI research, including window graphics, hand-held control devices and function menus that make computers more accessible to novices, and the capacity to recognize human speech for machine commands. Other AI offshoots include increasingly powerful robot control systems that are bringing three-dimensional vision to mobile, programmable machines, promising to further relieve workers of dangerous or discomforting jobs.

One element of AI that promises to greatly enlarge the capabilities of computers in electric utility applications is the knowledge-based expert system. As this month's cover story explains, an expert system program is designed not to process numbers but to process information, according to rules and logic derived from actual practice and experience. With this new kind of software, numerous opportunities arise for capturing, preserving, and more widely distributing some of the knowledge of humans who are expert in specialized technical fields.

Electric utilities are increasingly aware of the value of accumulated knowledge and experience in designing, operating, and maintaining power plants and power systems. As knowledge branches out and becomes more specialized, the accumulated learning of a veteran reactor operator or journeyman maintenance engineer becomes a scarce resource well worth preserving. Expert systems offer a means of doing that, as well as making that expertise more widely accessible. EPRI views the promise of artificial intelligence—including robotics and expert systems—as a new set of tools to aid utility personnel, amplifying their expertise in such a way as to reinforce, not replace, human capabilities.

As part of its beginning R&D effort in expert systems, EPRI developed a prototype system for a nuclear power plant application: analysis of a type of reactor transient in which some automatic safety features may not function as designed. The prototype's success convinced us that there are many possible uses of expert systems for a wide range of utility applications. Three R&D divisions now have substantial programs under way on expert systems for nuclear power applications, power systems operation and analysis, and gas turbine maintenance troubleshooting. Other divisions are also exploring possible applications in fossil-fuel-fired plants, economic and environmental analyses, and other areas.

On the basis of our experience to date with commercial expert systems development software, we believe that, in many cases, there is a real potential for utilities to build their own specialized expert systems largely in-house. Generic expert systems will also play a role, but because of utilities' individual technical, economic, and operational conditions, most will want systems specifically customized to their needs. We believe such customization is, indeed, possible.

To foster this development, EPRI hopes to transfer artificial intelligence techniques and tools directly to the utility industry, which has long written much of its own conventional computer software with resident programmers. With EPRI serving in an intermediary, technology transfer role, utilities should not have to wait for the commercial artificial intelligence software community to learn the intricacies and subtleties of power engineering, reactor physics, and the like.

Because of the many possible applications for expert systems in utility operations, we have established an Artificial Intelligence Coordination Committee at EPRI, with representatives from each of the six technical divisions. Part of the committee's aim is to ensure the full exploitation of the limited funds available for expert systems development.

Expert systems and their related subfields in artificial intelligence are truly exciting developments that promise to increase the productivity and accessibility of limited human resources in one of the largest, most knowledge-intensive of the nation's industries. Yet we must be careful that their potential is not overstated, that their maturity is not heralded too soon, and that their limitations are not overlooked. These considerations demand an aggressive, but well-monitored, approach to expert systems development—an approach that EPRI is enthusiastically pursuing with the utility industry.

Richard E. Balzhiser, Senior Vice President
Research and Development Group

Authors and Articles

With the advent of computers that can manipulate both symbols and logic, truly expert systems are taking shape. **Artificial Intelligence: Human Expertise From Machines** (page 6) explains how this form of artificial intelligence has special applicability for electric utilities in the information-heavy contexts of power plant operation, maintenance, dispatch, shutdown, diagnosis, and response to equipment malfunction. Taylor Moore, senior feature writer for the *Journal*, turned to many EPRI sources for information—especially to David Cain, Bill K.-H. Sun, Clark Dohner, and Mario Pereira.

Cain has been with EPRI's Nuclear Power Division since August 1974, most of that time in the Safety Technology Department, where he is now a program manager in computer applications for safety control and testing. Between 1981 and the latter part of 1983 he worked with the Nuclear Safety Analysis Center on safety displays and instrumentation systems for power plant control rooms. Cain was at one time with the naval reactors division of Westinghouse Electric Corp. He has a BS in electrical engineering from the University of California at Berkeley and an MS and a PhD from the University of Washington.

Bill K.-H. Sun, also a program manager in safety control and testing, joined the Nuclear Power Division in February 1977 after over four years with General Electric Co., where he became a technical group leader. Sun's work has always involved thermal-hydraulics analysis in BWR safety systems. He is a mechanical engineer with a BS from the National Taiwan University, an MS from the University of Kentucky, and a PhD from the University of California at Berkeley.

Clark Dohner, a project manager in the Advanced Power Systems Division, has been with EPRI since March 1982, guiding R&D in combustion turbines. He formerly was with General Electric Co. for 20 years, first in aerospace engineering and later, for 10 years, in the gas turbine division. Dohner is a mechanical engineering graduate of Johns Hopkins University, and he has an MS from the University of Pittsburgh.

Mario Pereira, a senior research engineer for Brazil's Electric Power Research Center (CEPEL) since 1976, came to EPRI on loan in September 1983. As a project manager in the Power System Planning and Operations Program of the Electrical Systems Division, he is involved in studies and software developments similar to his work for CEPEL—such as generation expansion planning, multi-area reliability evaluation, and transmission expansion planning. Pereira graduated in electrical engineering from the Catholic University of Rio de Janeiro; he later earned an MS in systems engineering at the Federal University of Rio de Janeiro.

■

When acid rain falls, it is only part of an intricate and variable sequence of phenomena. **Lake Sensitivity to Acid Rain** (page 16) reviews a seven-year research effort to sort out at least some of those phenomena and correlate them in a useful mathematical model. The article is the work of science writer Joel Shurkin, in cooperation with Robert Goldstein of EPRI's Energy Analysis and Environment Division.

Goldstein is a project manager in the Ecological Studies Program, where his major research responsibility is atmospheric deposition. Before joining EPRI in April 1975, he was a theoretical ecologist engaged in modeling studies for the environmental sciences division of Oak Ridge National Laboratory. Goldstein holds BS and MS degrees in nuclear science and engineering from Columbia University, and he also earned a PhD in engineering science there.

■

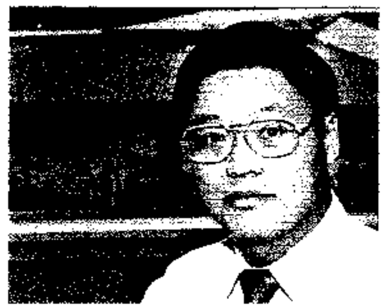
Education in economics during his university years and legislative experience during the energy crisis transformed an Iowa farm proprietor into a state utility commissioner with a national role in regulatory affairs. **Andrew Varley: Grounded in Economics** (page 22) presents impressions gained by Ralph Whitaker, the *Journal*'s feature editor, during an interview with Varley.

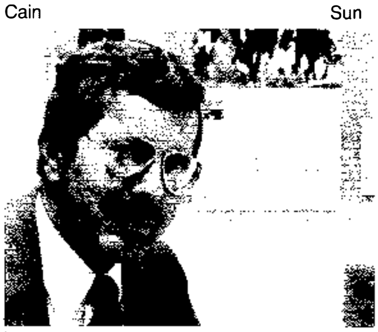
■

Not surprisingly, field-made splices have been the weak spot in underground cable performance, especially at the electrical stress levels of transmission voltage. **Factory-Molded Cable Joints** (page 28) describes the newest and best solution, factory-made components for field assembly. The author, science writer Stephen Tracy, was aided by Felipe Garcia, EPRI's project manager for the development.

Garcia has been a project manager in EPRI's Underground Transmission Program since 1975; in April of this year he moved to Yonkers, New York, where he continues his work at EPRI's newly acquired EHV Laboratory for testing transmission cable and related equipment. Before 1975 Garcia was assistant R&D director at the same facility, then owned by Phelps Dodge Cable & Wire Co., his employer for four years. Still earlier, he was with General Cable Corp. for 10 years. Garcia is an electrical engineering graduate of Carnegie Institute of Technology (now Carnegie-Mellon University).


Cain


Sun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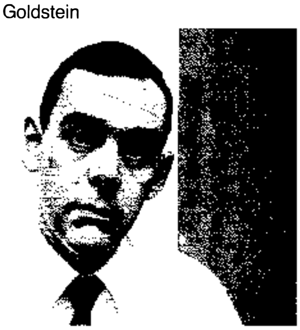
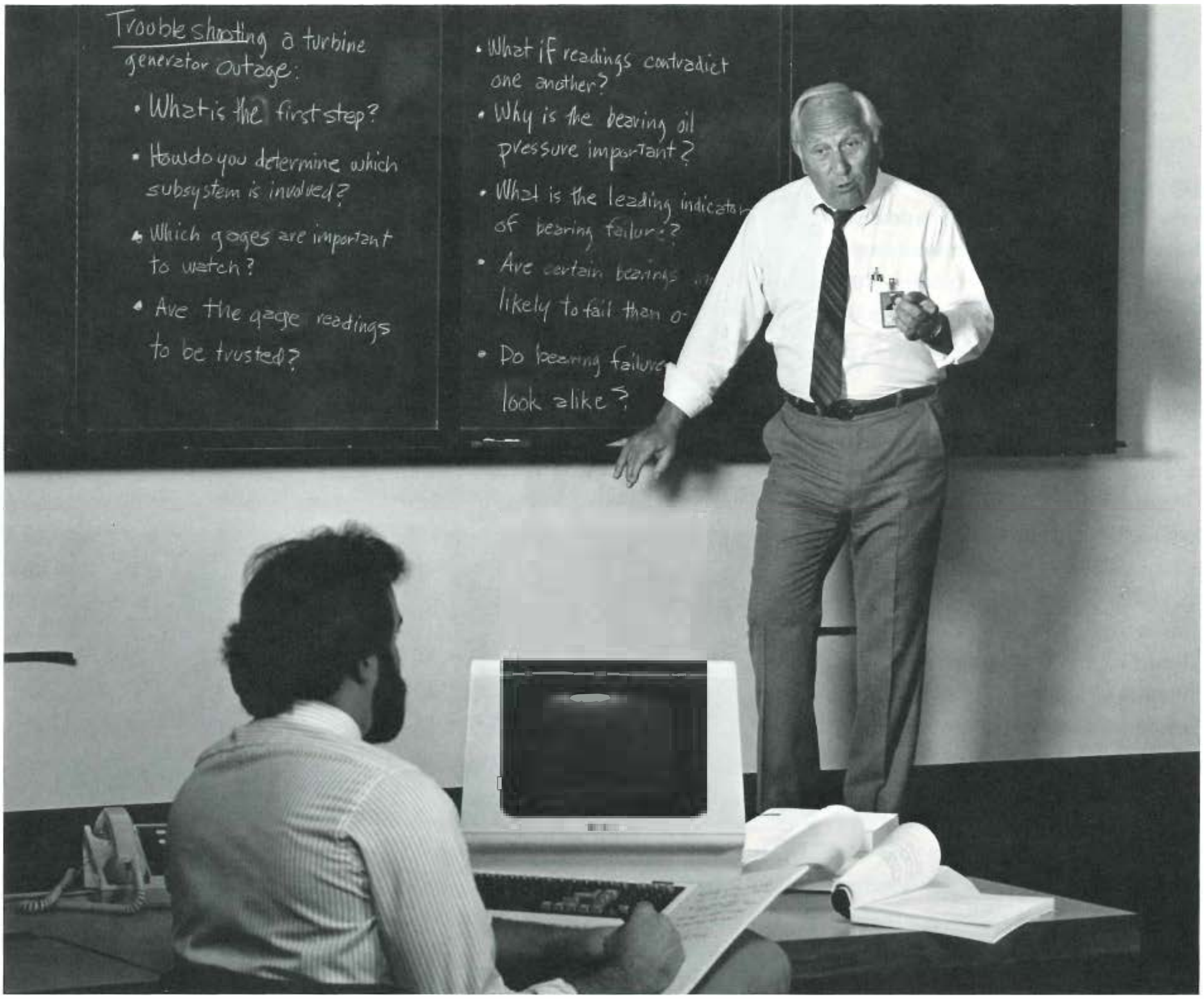

Garcia

ARTIFICIAL INTELLIGENCE: HUMAN EXPERTISE FROM MACHINES



Expert systems are designed to capture and emulate the knowledge, reasoning, and judgment of humans in highly specialized fields. EPRI has launched a broad-based exploration of potential applications intended to augment the diagnostic and decision-making capabilities of utility personnel.

Perhaps in the not too distant future, when a power plant control room operator needs the advice of his utility's best expert on shutdown procedures in the middle of the night, he won't need to pick up the telephone. Instead, he will select a magnetic floppy disk and consult with the expert's alter ego via computer in the time it takes a terminal screen to flicker.

Likewise, when one of the utility's gas turbines is forced out of service by an unknown cause and the company's most experienced maintenance troubleshooter is on vacation, the substitute foreman may ask a computer for help in identifying the possible origins of the outage and in determining the most likely culprit. The on-line expert, working from a base of knowledge and logic extracted from that of the real but unavailable expert, will also tell the foreman why and how it arrives at its conclusion.

Such scenarios and dozens of others like them are already in practice in many of the nation's government, university, and corporate computer science laboratories. Long barely more than a dream of computer scientists, artificial intelligence (AI) has blossomed in recent years. AI research has spawned a host of technological advancements, from window graphics for personal computers to robotics, machine sensing and vision, human speech recognition and synthesis, and expert systems that capture some of the knowledge and emulate the logical reasoning of humans.

Numerous AI companies, many of them building on experience gained in pioneering research funded by the Pentagon for military application, have formed to develop and market expert systems for a variety of professions that are increasingly knowledge-intensive, including medicine, petroleum geology, complex systems engineering, and computer software programming itself.

EPRI believes expert systems have a significant potential for aiding engineers and operators in a number of important procedures and operations that electric utilities frequently encounter. The areas of potential benefit range from numerous functions in nuclear power plant operations to maintenance troubleshooting for major plant components, as well as monitoring and diagnosis of entire power systems. Although the performance of such expert systems and the predicted speed with which they find their way into everyday application are easily overstated, research to date confirms that the basic premises of applying artificial intelligence tools to utility operations are, indeed, valid.

Three of EPRI's technical R&D divisions already have substantive projects under way to explore and develop expert systems for specialized applications. Other divisions indicate that AI tools are among their priorities for future research. Moreover, in recognition of the broad spectrum of potential uses of AI by the utility industry, the Institute has established a special coordinating committee to ensure cross-fertilization of research insights as well as guide the diverse efforts toward a common goal of delivering proven, reliable, and ready-to-use AI software tools for industry use.

Birth of a notion

According to one account, the origin of the computer science field of artificial intelligence, as well as the first offspring of one of its subfields—expert systems—can be traced to a meeting of a handful of university and corporate researchers at Dartmouth College in 1956. There, the phrase artificial intelligence was born and the development of a computer program called Logic Theorist, which was designed to prove difficult mathematical theorems, was announced.

Yet it would be some 15 years before a practical, commercial expert system emerged. In the intervening years, scientists wrestled with the limited but steadily advancing power of computer processing, the development of innovative and more-efficient programming techniques, and the resulting new software that permitted the processing and manipulation of symbols in addition to numerical data. Much of the leading-edge research in AI in those years, as it is today, was funded by the military for application to the varied and immense computational problems associated with large weapons systems design and control.

In addition to the symbolic versus numerical distinction, two other fundamental differences set AI apart from traditional computer technologies. First, AI addresses problems of structuring large amounts of knowledge and representing relationships with rules and semantic frameworks rather than with mathematical equations. Second, AI is convergent rather than divergent. Whereas conventional computer applications use relatively small quantities of input to generate large output, AI generally reduces large amounts of input to establish a few major conclusions.

In most areas of AI, including robotics, machine vision and sensing, and human speech recognition and synthesis, computer control programs fall far short of matching the competence or power of humans. But the key aspects that distinguish AI from conventional applications make one area of AI development—expert systems—potentially well-suited to problem-solving in narrow, specialized fields requiring knowledge-intensive and scarce expertise. In such applications, expert systems can assist the human user in analyzing alternative outcomes from a complicated set of conditions and, on the basis of specific knowledge about the problem at hand, determine the most likely successful path to a desired result.

When those fields involve stressful situations and little time for decision making to avert emergencies, as do many functions familiar to electric utilities, the potential value of expert systems becomes even more evident. Since the 1979 accident at the Three Mile Island nuclear power plant, there has been a growing recognition that human factors can be as important a limit in maintaining and operating power plants and power systems as the machines and computers involved.

"Our common goal within the electric utility industry has been to advance the state of the art to provide safer, cheaper, and more reliable electric power," explained Walter Loewenstein, deputy director of EPRI's Nuclear Power Division at an Institute workshop last year on artificial intelligence and expert systems. "State of the art includes the underlying physics and engineering principles as well as expertise. The power industry has spent enormous sums of money building tools that reflect these principles. Whereas the tools, such as sophisticated engineering codes, can be replicated rather cheaply, the skills to apply them cannot. We are increasingly stymied in efforts to move the state of the art forward by the fact that expertise remains a limited commodity.

"The expert system using artificial intelligence techniques is a promising way to capture the skills and knowledge from experts and may be used to enhance human capability for reasoning and diagnosis in various engineering and operations functions," Loewenstein added.

But as Loewenstein and other EPRI research managers are quick to point out, expert systems are by no means mature in development and suffer some distinct limitations—for example, the domain of expertise in which a system can be designed to operate is narrow, the language used to represent knowledge is limited to certain kinds of facts and relations, and programming is usually done in specialized and not widely familiar languages, such as LISP (list processing) or PROLOG (programming in logic). In addition, the extraction of knowledge from an expert and its construction in a knowledge base can be laborious and time-consuming, usually requiring extended interaction between a so-called knowledge engineer who is familiar with expert systems programming and a professional who is expert in a specialized application.

Expert systems can also have a hard time resolving conflicts between overlapping knowledge from more than one expert. Ideally, the expertise of several specialists could be encoded to a program, but if the experts don't agree, the logic becomes confused. In the same vein, expert systems are said to be fragile at the knowledge domain boundaries, meaning they aren't smart enough to know when they don't know enough to solve a problem. They just keep churning away, usually arriving at a wrong—even nonsensical—conclusion.

Perhaps most importantly, expert systems can give an illusion of expertise based on superficial knowledge while lacking the subtleties and insights of the deep knowledge humans acquire over a long professional career. It is unlikely that expert systems will ever be able to faithfully mimic such human intellectual qualities as intuition and common sense. Shortcomings notwithstanding, however, expert systems can be invaluable in raising issues that a decision maker may have missed.

Expert systems and AI research have received considerable attention in the general and trade media in recent years, some of it critical of the claims and promises made for the emerging technology. Some observers explain the gap between the promise of expert systems and the limitations of the current state of the art as merely evidence of the transition AI is making from science to engineering. AI researchers readily acknowledge that some challenging steps remain from the laboratory to the factory floor, power plant control room, or corporate boardroom.

But the promise and potential contribution of expert systems is such that, given the right combination of resources, computer science expertise, and practical experience in actual engineering applications, the lessons learned from AI research to date could lead to prodigious achievements. AI researchers point out that, despite their limitations, expert systems do not tire, sleep, or take coffee breaks; they don't forget, they don't have bad days, and they don't get emotional or frantic under stress. Their ability to recall vastly more encoded knowledge than any human can hold in memory is perhaps their strongest suit.

EPRI's initial AI efforts

Three EPRI R&D divisions have significant projects under way to develop expert systems for a number of potential electric utility applications. The Institute's initiative in AI picked up steam in late 1983 with increased funding authorization in response to growing interest in the field among EPRI's industry advisers.

The first significant EPRI work in expert systems, however, preceded the current projects by several years. In 1976, the Nuclear Power Division initiated a project with Shaker Research Corp. (a unit of Mechanical Technology, Inc.) and Northeast Utilities to develop a system for nuclear power plants to continuously monitor vibration in large pumps and automatically diagnose malfunctions. The effort focused on a system that could imitate an experienced machinery analyst, incorporating data from models, analyzing changes in vibration, and diagnosing malfunctions using the analyst's deductive reasoning.

Such a system, incorporating some 22 sensors tied to a minicomputer with associated analytic equipment plus software written in FORTRAN IV, was built and installed at Northeast Utilities' Millstone Unit 2 at Waterford, Connecticut, in mid 1978. The system was oper-

Interrogating the Expert System

In the future, power plant operators will be able to call up on-the-spot advice from expert computer systems that emulate the logic and knowledge of seasoned experts. A hypothetical exchange between an operator and an expert system might sound like this:

User:	Our turbine generator has tripped for no apparent reason. What should we do to determine the cause?
Expert system:	First, check sensors for alarms. Then, determine which subsystem is involved by comparing . . . Watch for false readings of lubricating oil pressure. If bearing temperature exceeds $x°$, it is a leading indicator of bearing failure . . . But if . . .

ated over several years, ending in May 1983 when the plant was brought offline for refueling.

According to Gordon Shugars, the EPRI project manager, the effort was largely a success; although the expert system did not uncover any serious pump malfunctions, it demonstrated an ability to detect malfunctions that would otherwise manifest themselves only during abnormal operation. Perhaps more importantly, the plant staff used the system to determine that no maintenance was required on reactor coolant pumps during an approaching refueling outage, thus saving extra outage time and avoiding some personnel radiation exposure.

Shugars points out that the automated diagnostic system is not a true expert system in the commonly accepted definition of the term. Because the software was written in FORTRAN, a cumbersome language for programming rule-based processing, changing any single rule required the programmer to manually verify consistency with all other rules. Expert programs written in AI languages such as LISP can automatically adjust themselves for consistency as new rules and knowledge are added.

The project also highlighted some of the difficulties involved with installing and maintaining a computer-based monitoring system inside a power plant, including physical and electrical environments, as well as cost considerations. "Utilities have to compare the costs and benefits of continuous monitoring systems with those of less expensive alternatives, such as periodic sampling with hand-held monitors combined with data analysis on personal computers," adds Shugars. A current follow-on project is focusing on such cost comparisons.

Encouraged by the success of the machinery diagnostic system, the Nuclear Power Division developed a prototype of an expert system for detecting and analyzing abnormal BWR shutdowns as part of a broader program to produce advanced operator decision aids. It incorporates knowledge about BWR plant design and component behavior, as well as knowledge required to distinguish normal, abnormal, and anticipated-transient-without-scram (ATWS) accident conditions. Developed inhouse using a commercial software tool known as the knowledge engineering environment (KEE), the BWR shutdown analyzer was programmed in LISP on a computer specially designed for AI applications and featuring window graphics and a mouse controller.

According to David Cain, an EPRI project manager for several current AI efforts and the shutdown analyzer's builder, the expert system was designed to assist a reactor operator in making quick sense of as many as 250 alarms that can be activated during plant trip conditions. "The ATWS class of accidents is one of the most serious that might occur in a nuclear plant," says Cain. "It is also one of the most demanding; an operator must recognize that the automatic reactor shutdown system has failed and take timely corrective action."

As a demonstration, the system was an eminent success; a videotape of it in action sparked considerable interest among utility advisers and other EPRI divisions. But the experience also produced invaluable insight on expert systems that will benefit current nuclear division projects for other applications, as well as efforts in other divisions.

On the plus side, says Cain, the LISP programming language and KEE commercial systems development tool are powerful media for developing knowledge-based expert systems. They even offer the potential for engineering experts to custom-design systems by themselves. "This is particularly important when there are very few people who know and can directly apply both AI and nuclear power technologies," Cain adds.

On the other hand, LISP is very different from the programming languages commonly used in engineering, and users proficient in FORTRAN should not expect to learn LISP easily by analogy. Although they can be made to operate on conventional minicomputers, LISP programs run best on compact dedicated LISP machines that cost from $20,000 to $100,000.

Moreover, LISP is an awkward language for doing numerical calculations. Although LISP-based programs can be and have been successfully integrated with FORTRAN programs running on conventional computers, development of a common interface may be a more practical solution.

Some experts predict that such integration may evolve from efforts to develop hybrid computer systems or innovative computer architectures that incorporate multiple parallel processing—so-called fifth generation enhancements that are being pursued in the United States and Japan. The challenge to integrate symbolic processing with numerical processing is particularly important in such fields as power systems engineering, in which FORTRAN programs have been widely used for some 20 years.

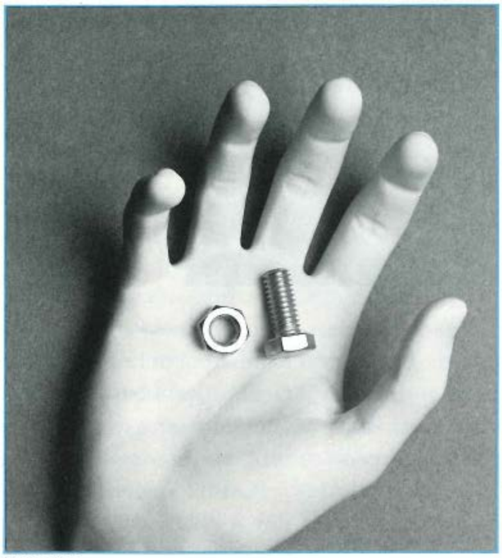
Current nuclear efforts

The shutdown analyzer's success as a demonstration prototype has led to a series of projects in the Nuclear Power Division aimed at producing commercial expert system software tools that utilities could use to custom-design their own expert systems for a spectrum of applications in and beyond nuclear plant operations. EPRI has contracted with IntelliCorp, maker of the KEE tool used to build the BWR shutdown analyzer, to develop an enhanced version for utility applications (EPRI-KEE).

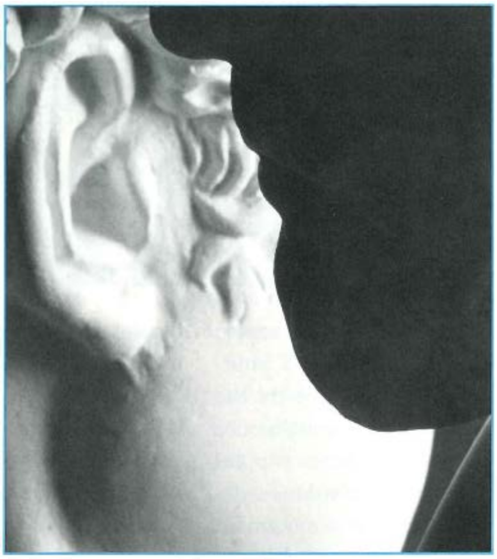
"The goal is that applications can be developed not by AI firms but by the utilities themselves. We want to transfer the technology from the AI community directly to our members and con-

The Four Fields of Artificial Intelligence

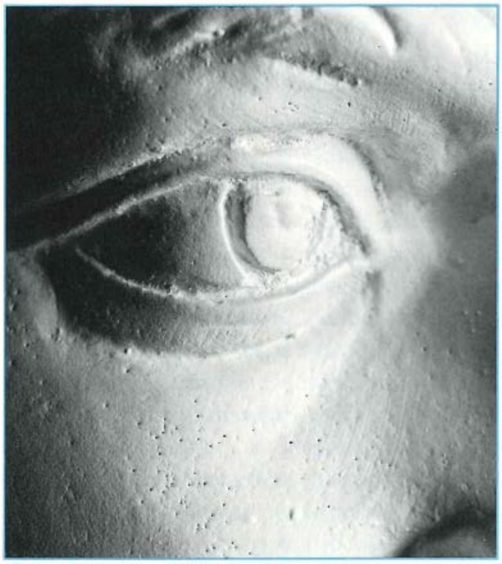
Artificial intelligence seeks to emulate human anatomy and thought processes by applying computer science, electronics, and mechanical engineering to the development of robotics, computers that understand natural language, machine vision systems, and knowledge-based expert programs. Integration of these four fields will someday produce the robots of today's science fiction.



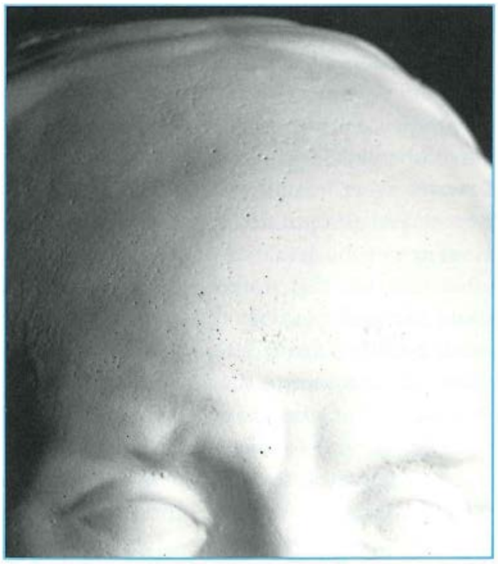
Robotics



Natural language understanding

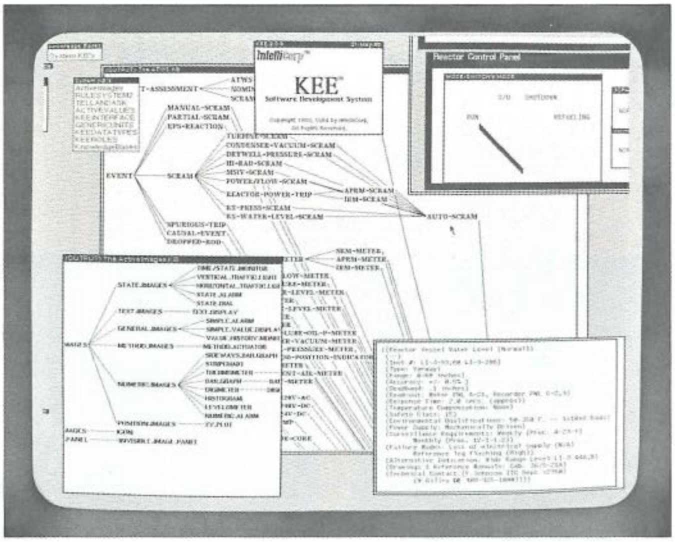


Machine vision



Expert computer systems

AN EXPERT FOR BWR SHUTDOWN ANALYSIS



EPRI developed a prototype expert system for analyzing BWR shutdown conditions to demonstrate the application of artificial intelligence techniques to nuclear power plant problems. The system combines declarative knowledge such as sensor ranges and trip set points with procedural knowledge such as the interactions between reactor scram components and rules for diagnosing malfunctions.

For the prototype, shutdown sequences and malfunctions based on a BWR plant model were simulated. The simulations served as input to the expert system in lieu of the actual online plant monitoring data that would normally tie into the analyzer. When run on a Xerox 1108 LISP machine, the system simulates reactor control displays commonly found in plant control rooms.

A user interacts with the system in several ways: by typing commands directly into a window on the display screen, by using a mouse controller device to select from menus, and by pointing to graphic elements on the display and changing values using the mouse device.

The prototype shutdown analyzer was developed—with about three man-months of effort—to demonstrate the capability of applying AI techniques using a commercially available programming tool: IntelliCorp's knowledge engineering environment (KEE). The knowledge base consists of 85 symbolic representations of reactor components and interrelations, along with about 225 rules that are constructed in an *if-then* mode. (For example: *If* the reactor pressure meter value is greater than 1055, *then* scram demand is present.) A fully developed shutdown analyzer might include as many as 2000 such rules.

Using the rules and knowledge of BWRs and shutdown conditions that have been programmed into it, the expert system is able to store and reconstruct the reasoning by which it established whether a hypothesis is valid or invalid. Or, the user can create a window within the display and examine the rules and conclusions as they are being processed by the system. This feature not only serves as a debugging facility, but also enables the user to audit the reasoning process as it progresses.

Possible extensions of the shutdown analyzer that were not developed for the prototype but are considered essential for a successful commercial system include a query routine that allows an operator to interrogate the system and obtain both plant encyclopedic information (component specifications, etc.) and the relevant emergency procedures necessary to restore the reactor following a transient.

"The concept illustrated with the prototype would have to be broadened and made more robust before actual plant installation could be considered," says project manager David Cain. "One important unresolved issue is validation, an essential ingredient in safety-related nuclear applications. How can you be sure that the program made the correct conclusion? There appears to be no easy solution to the validation problem." □

tractors, who know and understand the specific problems of nuclear plants or fossil-fuel-fired plants and other kinds of electric power installations. We're serving as the technology transfer agent between the AI community and our industry,'' Cain explains.

EPRI's expert system development tools and a methodology handbook for programmers will be available to members through the Electric Power Software Center, possibly within a year. "There's still the task of building an expert system. You have to decide how to represent the knowledge, kind of like building a data base, and how you're going to incorporate the procedural rules into the system. But once you've got that on paper, this type of software tool provides the programming environment for rapidly prototyping and implementing a system," adds Cain. Commonwealth Edison Co. and Duke Power Co. engineers are working with EPRI as advisers in defining functional specifications for the software tools.

Related projects will evaluate other possible nuclear applications. "One application we've looked at that is a classic expert system problem has to do with reactor fuel shuffling," says Cain. "How you rearrange fuel during refueling to get more complete burnup of unfissioned fuel is a bit of a black art. You can run elaborate, highly iterative pin-by-pin calculations, but an expert system could guide a utility in the analysis, reducing the number of iterations required from 20 or 30 to 2 or 3."

The decentralized approach embodied in EPRI's effort to develop expert system software tools is in contrast to an alternative, more centralized approach to AI applications represented by the on-line AI diagnostic service offered by Westinghouse Electric Corp. The power equipment vendor has established a diagnostic center at its Steam Turbine-Generator Division headquarters in Orlando, Florida, that is capable of receiving up to 100 on-line monitoring signals from a utility turbine by telephone line or satellite for immediate analysis by Westinghouse experts backed up by powerful turbine diagnostic software.

Other nuclear plant applications of expert systems under study at EPRI include an on-line procedures analyzer as a kind of desktop adviser, permitting plant operators to scan quickly the relevant procedures for a number of possible emergency situations. "A slightly different application would provide guidance in managing a maintenance outage, planning within constraints on plant conditions, time, personnel, and materials," says Cain.

Still other applications include monitoring of technical specifications for complying with regulatory requirements for surveillance and inspection; water chemistry maintenance; plant startup procedures; signal validation for monitoring systems; advanced training aids tied to plant simulators; event-tree analysis used in probabilistic risk assessment studies; and as the reasoning faculties of advanced, semiautonomous robots for plant inspection and maintenance.

Other work at EPRI

EPRI's Advanced Power Systems (APS) and Electrical Systems (ES) divisions are also involved in expert systems projects. General Electric Co., Honeywell, Inc., and Arinc Research Corp. are the contractors on an APS project to develop an expert system for troubleshooting and maintaining gas turbines. The goal is to reduce the number of forced outages on gas turbines, fully half of which are of unknown cause.

Clark Dohner, APS project manager, says rules are now being assembled for the system after about five basic tasks were identified this year. Installation and on-line operation of a prototype gas turbine maintenance troubleshooter are planned early next year at Jersey Central Power & Light Co.'s Gilbert combined-cycle station. Dohner says the system will be used initially for locating ground faults and diagnosing combustion problems. Arinc Research Corp.'s role will be to develop a methodology for determining the value of benefits from using the expert system.

General Electric, which is responsible for the software development, already has some experience in expert systems; another unit of the company produces and markets a system called DELTA (diesel electric troubleshooting aid) for field maintenance of locomotives. The gas turbine expert system is being designed to operate on IBM personal computers.

In addition to the gas turbine work, the APS Division is looking to expert systems as a means of preserving the experience and knowledge gained in operating the country's first utility-scale gasification–combined-cycle power plant: Southern California Edison Co.'s Cool Water facility near Barstow. EPRI and the other Cool Water project sponsors have begun work to develop an expert system for specific subsystems of the Cool Water plant.

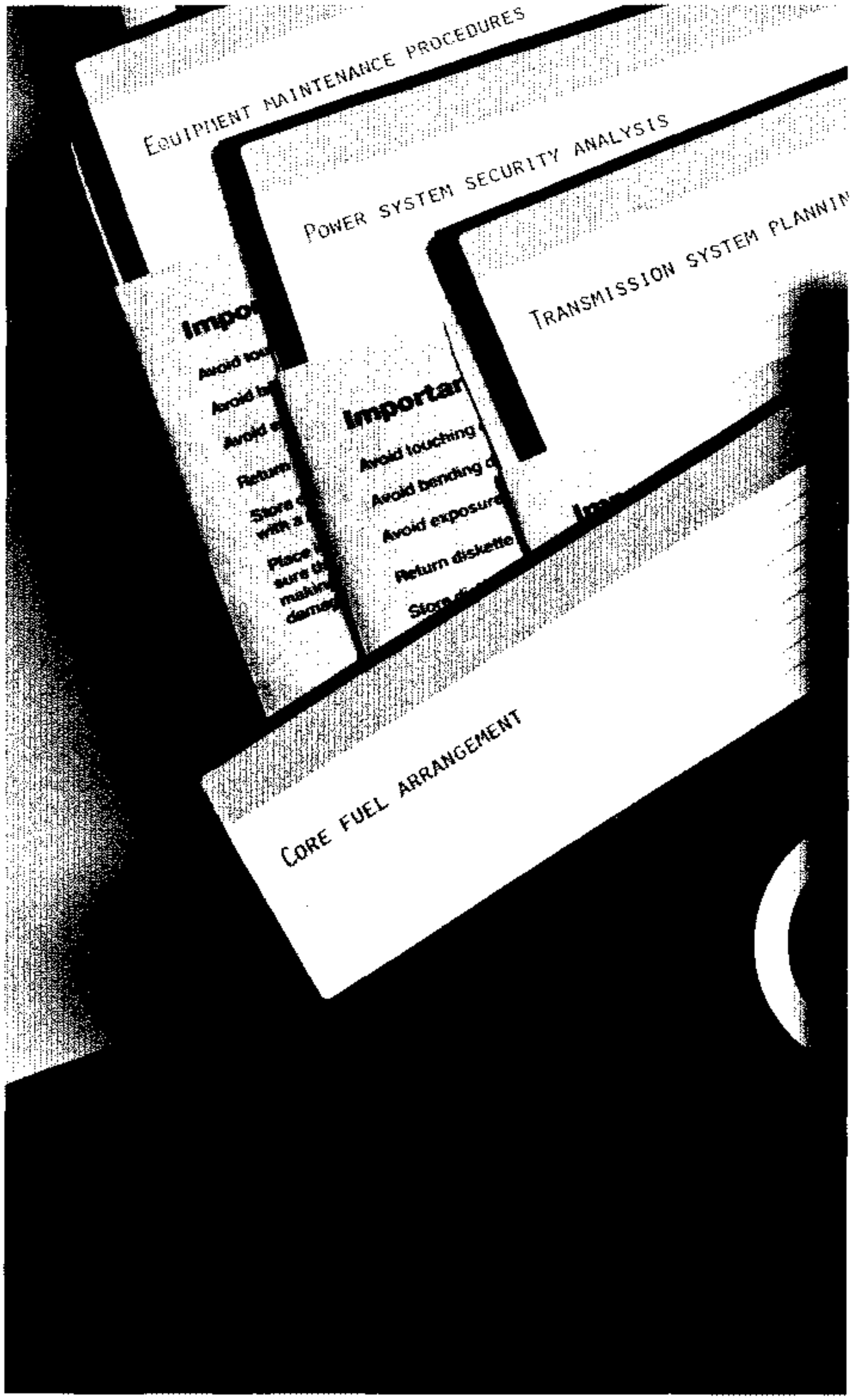
Expert systems have a wide range of potential application to power systems operation, including emergency control, contingency analysis, and security analysis. The Power System Planning and Operations Program in the ES division is completing a study with Carnegie-Mellon University's Design Research Center to evaluate applications and develop an expert system for troubleshooting transmission relays and breakers.

A demonstration prototype, containing about 600 rules and written in the AI language known as OPS-5 for running on a DEC VAX 11/780 computer, was recently completed. Allegheny Power System and Duquesne Light Co. are involved with EPRI in this effort.

A second contract with Union Electric Co. in conjunction with the University of Missouri at Rolla will replicate the CMU prototype in PROLOG, an AI language favored by the Japanese in their concurrent efforts to advance AI,

A Library of Desktop Experts

Expert systems offer a multitude of potential applications in the electric utility industry. Knowledge, rules, and procedures for a variety of specific domains can be preserved and duplicated on computer diskette for wide access and dissemination. As application programs are developed and tested, they could form a library of handy desktop advisers.



according to project manager Mario Pereira, who is on loan to EPRI from Centro de Pesquisas de Energia Eléctrica (CEPEL), the research arm of Brazil's utility industry.

PROLOG, considered a higher-level language for AI applications, incorporates some ability to make logical inferences that would have to be programmed explicitly in LISP-based systems. It also promises an easier transition to combined numerical and logic processing than is foreseen with LISP. "If PROLOG proves to be a reasonable language for integrating numerical processing with expert systems, then we plan to develop a system for voltage-VAR control applications, which are among the most complicated and urgent computational problems in power systems operations," says Pereira.

ES project managers Charles Frank and James Mitsche have identified several other possible applications of expert systems. In the area of system planning, these include an advanced software HELP function for helping trainees manipulate and control other programs, such as transient stability simulations; a software output analyzer for the thousands of cases created during a system expansion study; and a coordinated planning aid for integrating generation and transmission expansion analysis.

System operations pose a different set of potential applications. Expert systems could generate preventive action plans to respond to severe contingencies by incorporating experience accumulated from operating the power system. An adaptive capability could be designed into the system so that a preventive action plan could be modified during execution to account for changed conditions.

Other network operations amenable to expert system application include enhancement of existing operator training simulators to adjust simulations dynamically in response to unanticipated trainee actions; a powerful state estimator that could continue producing estimates of various system quantities despite the loss of some direct measurements; enhanced maintenance, fuel, and power transfer scheduling; and development of emergency system restoration procedures.

"Many power system planning and operations problems are ideal for expert system application because of the growing complexity of today's power networks," explains Pereira. "At the same time that power systems are becoming larger and more interconnected, operators must cope with a high degree of uncertainty and conflicting goals, such as those posed by environmental and security constraints. Expert systems could help manage the resulting information overload."

In addition to the myriad applications already mentioned in nuclear plant operations, gas turbine maintenance, and power system planning and operations, other EPRI divisions have also identified possible avenues in which expert systems could make a contribution by capturing and preserving knowledge. For example, expert systems could help lay out life extension and diagnostic procedures for fossil-fuel-fired power plants. The Energy Management and Utilization Division may also begin exploring the application of expert systems to industrial customer service.

The Energy Analysis and Environment Division has conducted a workshop to identify areas in energy and environmental analysis where AI technology could help. Potential applications range from systems to aid in responding to chemical spills to ones that encode expertise in demand forecasting. Scoping studies have been initiated to explore specific applications, including generation of procedural specifications for handling environmental emergencies; providing a quick response to inquiries on demand-side management activities; and integrating nonquantitative factors in investment allocation.

Coordinating the effort

With so many possible uses for expert systems in the utility industry and an increasing level of R&D attention among several EPRI divisions, it seems obvious that, if the efforts were coordinated, cross-fertilization of research results could yield a more-efficient use of resources. Such was the idea behind the establishment last year of the EPRI AI Coordination Committee, composed of representatives of each R&D division and chaired by Bill K.-H. Sun, a Nuclear Power Division program manager.

Under a charter from Richard Balzhiser, senior vice president for R&D, the committee meets periodically to exchange ideas and insights on current and planned projects, as well as to plan Institute workshops and seminars on AI applications. It keeps EPRI management informed about the status of related work at EPRI and about the constantly advancing state of the art as it develops around the country, including the area of the highest concentration of AI activity—EPRI's own backyard in Silicon Valley.

One example of the kind of coordination that can benefit all division research is the Nuclear Power Division project to develop expert systems software tools. Such tools could become a generic starting point for many applications development projects, as well as for ensuring consistency and compatibility among diverse applications. The ES division has, in fact, already benefited from the software tools development; its prototype expert system for transmission fault diagnosis, originally written by CMU in the OPS-5 language, was recently converted to the LISP-based KEE system at no cost to EPRI.

Another important role of the committee, as Sun explains, is to involve utilities in the early planning stages of AI projects to ensure that when applications products are developed, they satisfy clearly defined needs of the industry. "We're looking at getting AI technology into the hands of the utilities in one to three years," he says. "So it's important to get them involved in the beginning.

"Our goal is to help utilities build their own expert systems," adds Sun. "Twenty years from now, a lot of the industry's knowledge about operations, diagnostics, and maintenance will be on computer diskettes. For any of these fields, there is no single textbook or manual that can contain it all. A lot of practical utility experience in these areas now gets lost because people retire or change jobs. In a period in which there are virtually no new orders for generating plants, utilities are exploring more and more how to improve the performance of existing equipment. And with expert systems that can process information and knowledge, the potential for improving productivity is tremendous." ■

Further reading

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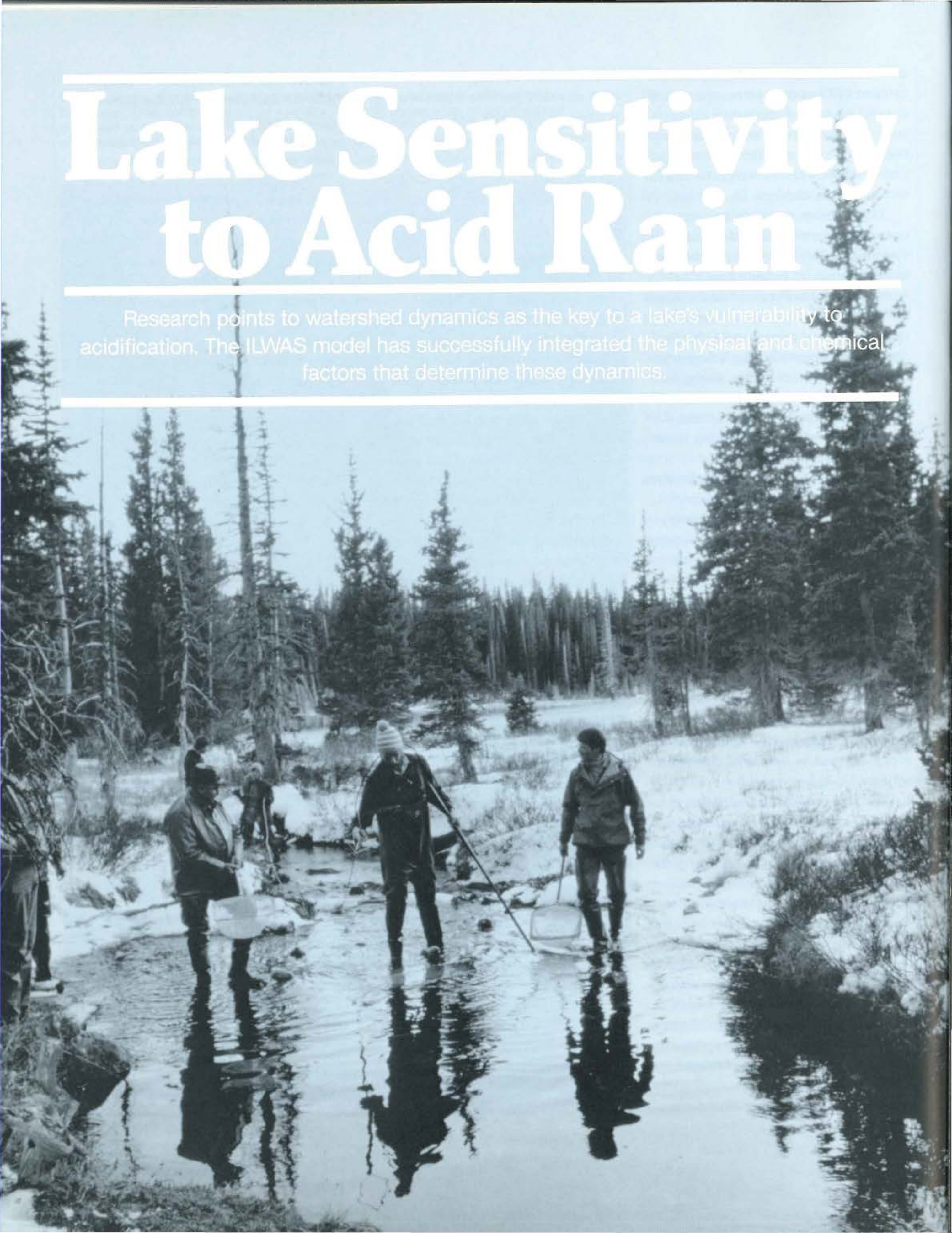
This article was written by Taylor Moore. Technical background information was provided by David Cain and Bill K.-H. Sun, Nuclear Power Division; Clark Dohner, Advanced Power Systems Division; and Mario Pereira, Electrical Systems Division.

Lake Sensitivity to Acid Rain

Research points to watershed dynamics as the key to a lake's vulnerability to acidification. The ILWAS model has successfully integrated the physical and chemical factors that determine these dynamics.



EPRI's Integrated Lake-Watershed Acidification Study (ILWAS) has produced a computer model that can accurately characterize the vulnerability of a lake region to acid rain. Not surprisingly, the model, which has been tested and modified in varied and complex ecosystems, is now being sought internationally by government agencies responsible for making environmental policy. On the way to producing that model, EPRI researchers and collaborators had to reach an unprecedented level of awareness of how watersheds work and how rain, soil, forests, and rocks interact.

"What we've developed is an assessment tool," says Project Manager Robert Goldstein. "We ourselves are not assessors; our function is research. The policy maker wants to know the sensitivity of surface waters in different regions to changes in deposition chemistry. The ILWAS model is an analytical tool that will guide whoever is charged with doing the assessment. If the assessor has the data, he or she can plug it in and do the analysis—straightforward. Without the data, the model becomes sort of a template or a guide to tell the assessor what data to collect."

The major scientific finding of the ILWAS research and its follow-up study, the Regional Integrated Lake-Watershed Acidification Study (RILWAS), was that lake acidification is vastly more complex than previously thought. Factors ranging from the depth of the soil to the steepness of the watershed, the nature of the forest, and the type of bedrock are all involved in a delicate and complex interplay that determines just how vulnerable lakes are to rainfall acidity.

Goldstein says the conceptual breakthrough of ILWAS was based on integration of information. Before this study, data on lake acidification were sparse and unreliable. It was clear that a problem existed, but the dynamics of the problem were either unknown or, it is now obvious, misunderstood. Contradictions in the data were not uncommon. And the question was further complicated by inherent, sometimes counterintuitive conflicts. In particular, why—in areas assumed to be vulnerable to acid deposition—are some lakes acid while others, seemingly alike, are not?

With rising publicity and public pressure over the issue of acid rain, EPRI entered the picture in 1977 with ILWAS. There were pressures to do the work quickly. Indeed, the final report states: "It is important to emphasize the long-term aspects of ILWAS." When ILWAS was first conceived, many individuals claimed that because of policy considerations the technical questions addressed by ILWAS had to be answered within six months. The individuals responsible for development of the study, however, recognized that such a short-term approach would be fruitless and that not even a one-year program could produce a "technically sound and adequate data base and theoretical framework for developing a general quantitative relationship between acidic deposition and lake acidity." ILWAS became unique in terms of the length of time for which intensive data were collected for such a wide range of biochemical aspects.

Theories to explain vulnerability abounded before ILWAS, mostly centered on the nature of the bedrock underlying the watershed. According to one theory, if the rock contained calcite or other buffering agents, the rock would act to neutralize acid that fell into the lake watershed from the rain. If the rock was nonreactive, like granite, the acidity was allowed to build up. But environmental researchers found many lakes in which this rule did not apply—lakes underlain with limestone bedrock that showed high acidity and granitic lakebeds that underlay neutral lakes.

To try to clear up the question of bedrock effects, the study selected three lakes, situated within 19 miles of each other, in New York State's beautiful Adirondack Mountains. The lakes have a similar granitic bedrock, yet exhibited different levels of pH. Woods Lake was highly acidic, Panther was neutral, and Sagamore fluctuated between the two but was generally neutral.

Into the area went what was, for environmental science at least, an army of researchers, including about a dozen principal investigators and a score of technicians and graduate students. The researchers came from Smith College, Colgate University, Rensselaer Polytechnic Institute, the University of Virginia, Brookhaven National Laboratory, the University of Maine, Tetra Tech, Inc., Cornell University, and the U.S. Geological Survey. The USGS also shared costs for the study.

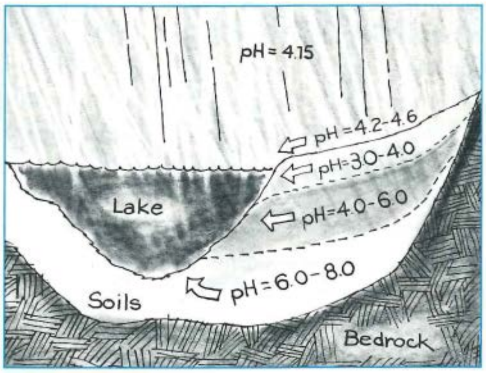
The watershed system was divided into a network of compartments for the purposes of the research: atmosphere, snowpack, canopy, vegetation, soil horizons, bogs, stream segments, and lakes. Goldstein likens the task of characterizing a lake's vulnerability to trying to put together a large jigsaw puzzle without all the pieces and without a guiding picture. Some pieces fit together, most did not, and many were missing.

The researchers' first task was to find the missing pieces. The first problem was to establish the level of acid in the rainwater and see if the differences in the lake had anything to do with the content of the rain. Special buckets were set up around the area, equipped with sensors that opened the lids when it rained. The buckets were kept covered the rest of the time to keep them free of any windborne particles. Laboratory tests of the water collected showed that the acidity of the rainwater falling in the three watersheds was the same.

The researchers also wanted to see if the acidity of rain was altered as it passed over leaves and plants in the forest before falling on the lakes and surrounding soil. Analysis showed that it was. Using plastic bottles with special funnels attached, the researchers collected, then studied, the rainwater as it dripped from the foliage. Analysis showed that dry, acidic materials in the air, either particu-

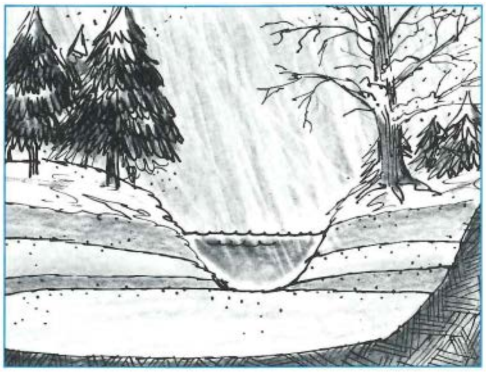
Watershed Dynamics

Hydrology, geology, soil composition, vegetation type, and climate are all important in the complex interplay that determines how vulnerable a lake is to rainfall acidity. The examples below, though much simplified, illustrate how these watershed factors can alter the pH of a lake.



Lake water pH can be influenced significantly by the depth to which precipitation seeps into the soil before flowing laterally into the lake; the degree of neutralization in each stratum depends in large part on the amount of exchangeable base cations and weatherable minerals in the soil. As a general rule, greater soil depth and permeability lead to greater neutralization.

Limestone bedrock, good soil depth, and a high concentration of base cations (e.g., calcium and magnesium) in the soil give this watershed an edge in neutralizing rainfall acidity. Interaction with the leaves and trunks of deciduous trees also works to lower the rainwater's acidity as it falls through the forest canopy.



Granite bedrock and low-base-cation soil decrease the watershed's ability to neutralize acidity, and frozen topsoil compounds the problem by limiting soil permeability. The coniferous trees in a mixed forest can actually increase rainwater acidity and cancel out the beneficial effects of broad-leafed trees.

An extreme case of a vulnerable lake might have shallow soil of low permeability (e.g., hard-packed clay), granite bedrock, and a predominance of conifers. A steep watershed incline increases the probability that acidic rainwater will flow directly into the lake rather than through the neutralizing soil.

late matter or gases, settle on the leaves and needles. When rainwater struck the foliage, the material was absorbed into the water, changing the pH of the rainwater that dripped to the ground. Natural materials from the trees, such as sap, also altered the water. The acidity of rainwater passing over evergreen foliage was increased by contact with the needles, whereas the acidity of water striking deciduous foliage was decreased.

Although this interesting mechanism added new data to the general model of lake acidification, it was not a significant piece of the Adirondack puzzle: the forest around all three test lakes is generally deciduous, yet the lakes differ in acidity.

Rainwater falling directly on a lake is not its only source of water, of course. Water drains into a lake through the soil, either through the shallow topsoil or the much deeper soils of the watershed. The water may be altered by chemicals it picks up from the soil as it flows through. Thus the ILWAS researchers had to determine the flow paths of the water that entered the three lakes and the portion of the water in each lake represented by each flow path.

At the outlet of each lake is a small dam with a V-shaped notch. Researchers calibrated the notches at regular intervals to measure the flow of water, which they then measured against a time scale. This hydrograph produced a picture of how much water flowed from each lake at any particular time. Particularly useful were fluctuations identifying storms or the spring runoff of melted snow; storm runoff or snowmelt does not have time to go very deep in its rush to a lakebed, and any acidification or buffering that occurs comes primarily from the topsoil. At other times of year, when water takes a more leisurely route downhill, it goes through the deeper soils and reflects the chemistry that occurs there.

The hydrographic data led to closer studies of the soil. Taking cores 2 inches in diameter, the researchers sampled the soil to considerable depths. They also dug pits, 4 feet long, 3 feet wide, and 3 feet deep to get another picture of the soil. Soil water samplers, called lysimeters, were buried in the field at depths of 2 feet or more to measure the concentrations of dissolved chemicals in the water as it flowed toward the lakes.

In the laboratory, tests were run on the soils to try to simulate what appeared to be happening in the field. For instance, rainwater was run through soil samples to see how the chemistry of the water was changed. In addition, the soil itself was studied in minute detail, using sophisticated equipment such as X-ray fluorescence and X-ray defraction devices. This research produced a detailed menu of the chemicals in the soil.

One outcome of these field and laboratory studies was the finding that some soils acted as buffers, taking certain ions out of the water, whereas some added ions. Other soils had no overall effects. With these pieces in place, the time came to put the puzzle together. Starting in 1982, the ILWAS researchers went to work on the final report and the computer model.

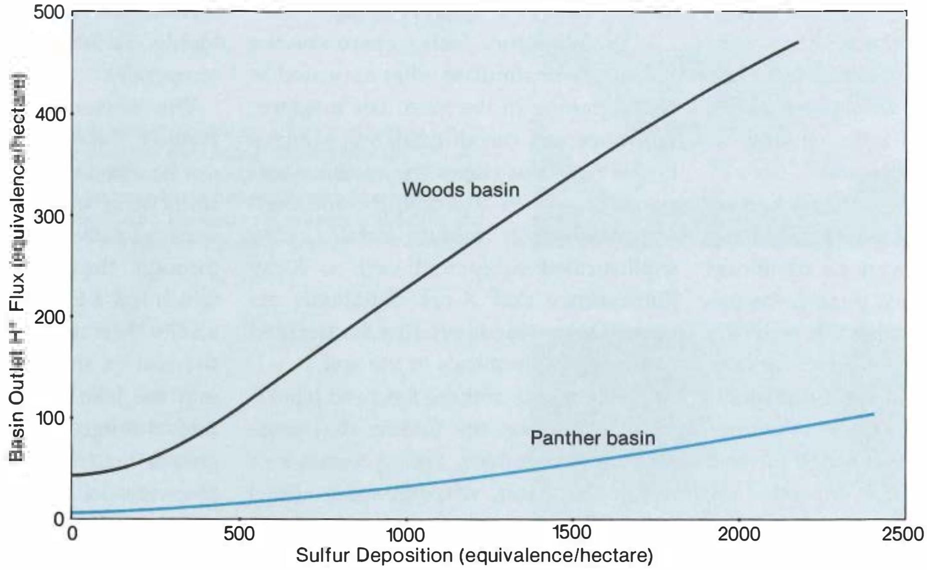
Teamwork was never more apparent, Goldstein said. "They functioned together, coordinated their data collections, and met at regular intervals to discuss with each other what they had learned. One of the problems, when it came time to do the final presentation of the study, was that everybody started to write the same paper. Everybody wanted to give the integrated conclusion, which each person thought he had derived himself. I think each person had derived it himself because of the interaction." The final report is a collegial effort, Goldstein says. "There was a convergence."

ILWAS found that the ability of a watershed as a whole to neutralize acid is the main determinant in assessing the vulnerability of a lake. All the results of ILWAS confirm the major hypothesis on which the study was based: that is, a lake's vulnerability to acidification by atmospheric deposition can be understood only in the context of the ecosystem—in particular, the biogeochemistry and hydrology of the entire catchment. As the final report states, "Acid-base status is determined by the interaction of many factors (e.g., soil, hydrology, vegetation, geology, climate, atmosphere), and the relative role of any one factor can be highly variable geographically . . . and temporally."

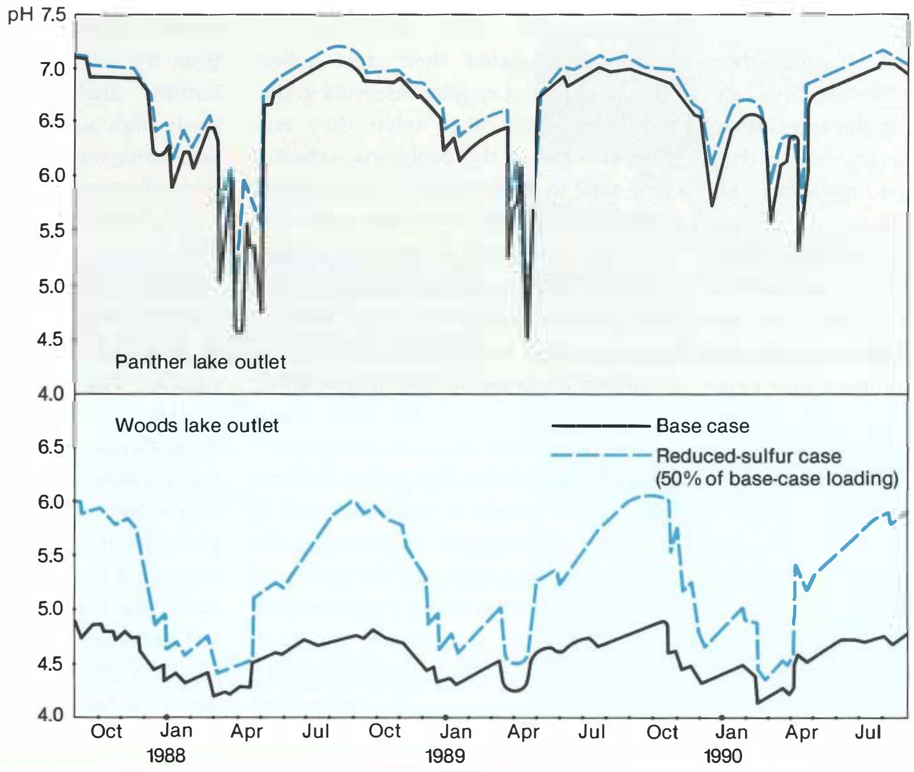
The seasonal change in acidity of Panther Lake demonstrates how time can be a factor. During snowmelt, when water runs quickly through the watershed, a relatively large proportion travels through the organically rich topsoil, which has a lower capacity to neutralize acidity than the deeper flow paths have; the rest of the year, rainwater coming into the lake travels in greater proportions through the deeper flow paths, and greater neutralization takes place. Also, the water in Panther Lake tends to become stratified during the winter, with the warmer water at the bottom and the colder toward the top. (As water cools, its density increases until it reaches 4°C; below that temperature, its density decreases.) At snowmelt the cold, acidic water entering the lake remains at the surface. Since the lake outflow draws from the surface, measurements of the outflow during snowmelt show relatively high acidity. However, as the surface water warms with the change in seasons, it becomes more dense and sinks, mixing with the less acidic water below. The result is a neutral pH at the outlet.

ILWAS data seemed to point to soil characteristics and rainwater flow path as important pieces of the acidification puzzle. For example, ILWAS found Woods Lake to be much more vulnerable than Panther, which has deep, porous soil capable of neutralizing acid in the rainwater. Woods's soil was just as porous but much shallower and hence contained fewer neutralizing agents. Indeed, the study's hydrologic and chemical analyses led to the general conclusion that the route of water through a watershed is a major determinant of lake water alkalinity and vulnerability to acidification by atmospheric deposition.

An ILWAS simulation of annual hydrogen flux at the outlets of the Woods and Panther watersheds predicts how changes in sulfur deposition affect the acidity of these lakes. The model shows marked differences between the two basins in both acidity and sensitivity to changes in sulfur loading, even though they share the same bedrock. In this case, the greater soil depth of the Panther basin explains its greater buffering capacity.



Woods Lake's greater sensitivity to acidification is again demonstrated in this ILWAS simulation of the effect of sulfur loading on lake outlet pH. When the amount of sulfur is halved, the Woods pH increases significantly, whereas the sulfur reduction produces a negligible change in high-pH Panther. The pronounced pH drops for both lakes in the early spring are brought on by snowmelt, which filters primarily through non-neutralizing topsoil.



The ILWAS model seemed to explain what happened in the Adirondacks region, but would the same principles hold true elsewhere? Another project, RILWAS, was set up to test the model derived from the ILWAS research. The purpose, Goldstein said, was to test the general applicability of the model, to increase the robustness of the model by applying it to more diverse situations. "In as complicated a phenomenon as this, certainly what you observe for three lakes is not going to be everything you need, although you'd like to think it's mostly there." RILWAS came with the ILWAS theoretical base to guide the researchers. Consequently, they had to gather fewer data.

One area tested is in western North Carolina, a watershed that doesn't have a lake, but rather is drained by a stream. Soils are much older there, as the area escaped the period of glaciation that determined the structure found in the Adirondacks, and have been weathered for much longer periods of time. Minerals in the North Carolina test area are more completely dissolved, and the watershed is also very steep. Because the North Carolina site consists of streams, not lakes, there a much faster response to precipitation than there is in the Adirondacks watershed.

In a further test, cofunded with Empire State Electric Energy Research Corp., the ILWAS researchers went back to the Adirondacks, this time to study large sections of the entire region. Instead of three lakes, close together and very similar, they studied 20 different watersheds spanning the entire range of environmental situations existing in the region. The lakes had different soil types and different vegetation. Despite these variations, the ILWAS model held.

In a Wisconsin test, the researchers chose yet another setting—two seepage lakes, lakes in which there is no surface inflow or outflow. The lakes are controlled by precipitation falling directly into them, and by fluctuations in the groundwater table—a situation very different hydrologically from that faced in New York State. ILWAS results seemed so promising that a consortium of Wisconsin utilities decided to cofund the test with the Wisconsin Department of Natural Resources and USGS. Such confidence was not misplaced—again the model stood up.

As expected, some modifications were required in translating the model for use in different settings, but the same basic model that seemed to explain the Adirondacks' vulnerability worked in the mountains of North Carolina as well as the lake country of Wisconsin. RILWAS also went to a few areas high in the Sierra Nevada for further testing, and additional work was done in Sweden.

Besides RILWAS, two other studies spun out of the original ILWAS work. One, the Paleoecological Investigation of Recent Lake Acidification, or PIRLA, uses the techniques of the paleoecologist to infer what the pH levels of lakes were in the past. It investigates the age of the sediment strata in lake beds, testing such things as lead 210, cesium 137, charcoal, and pollen. This study, which will be completed in 1986, is expected to offer researchers a better understanding of long-term acidification trends because it documents changes over decades or centuries rather than over a few years.

The other study is a test of methods to moderate or even neutralize bodies of water that are already acidic using artificially introduced buffering agents, such as lime. EPRI is trying to find out if the addition of liming agents will help lakes support fish populations that normally would not survive.

Goldstein believes the ILWAS model has other uses as well. It can be used to study the effects of atmospheric deposition on terrestrial vegetation. "The model can also be applied to studies on effects on aquatic biota, because it simulates the chemical environment in which the aquatic biota live."

In the meantime, ILWAS continues to gain recognition around the world. A number of utilities have already been licensed to use the model; among them are the Tennessee Valley Authority, Southern Company Services, Inc., Utah Power & Light Co., the New York Power Pool, Northern States Power Co., Public Service Co. of New Mexico, and Wisconsin Electric Power Co. Also, the following government agencies have asked for copies of the ILWAS model: the Environmental Protection Agency, Argonne National Laboratory, and Oak Ridge National Laboratory in the United States; the Swedish Environmental Research Institute; Wageningen Agricultural University of the Netherlands; and the International Institute of Applied Systems Analysis of Austria.

But in a broader sense, use of the model has really just begun. Robert Goldstein believes that the approach developed so successfully for ILWAS could well extend beyond the study of watershed dynamics to other ecological problems, such as the role of atmospheric pollutants in forest decline and the ecological effects of trace amounts of toxic substances. Using the ecosystem as a framework for technical integration, and concentrating on mechanisms and processes rather than on questionable historical data, the approach offers an interdisciplinary scientific team the opportunity to reach consensus—an outcome that is hard to achieve in any scientific endeavor. ■

This article was written by Joel Shurkin, science writer. Technical background information was provided by Robert Goldstein, Energy Analysis and Environment Division.

Andrew Varley: Grounded in Economics

The chairman of Iowa's Commerce Commission brings the perspective of economics to his twin pursuits of agriculture and utility regulation. As a member of EPRI's Advisory Council, Varley encourages research that is closer to the edge and that carries proper incentives for the use of new technology.

Springtime came to Iowa with sunshine and temperatures in the sixties this year. But the new season found farmers there—and elsewhere in the Midwest—with mixed feelings. Farm investments that were thoroughly prudent risks 10 years ago had come to be deadly burdens of debt. U.S. farm prices were down, export markets were disappearing because of the strength of the U.S. dollar, and land values—collateral for the loans of the seventies—had fallen as much as 70%.

In an ironic parallel, electric utilities are also haunted by decisions made 10 years ago. Big power plants have escalated in cost during construction, while—partly in consequence—electricity market growth has slowed to a crawl. When a regulated utility's new plant does not meet the test of "used and useful," its capital cost is not allowed in the rate base—that is, it does not appear in customer rates and must instead be borne by the utility and its stockholders.

Farm and utility financial crises both engage Andrew Varley. He operates Pine View Angus Farms, Inc., (cattle, corn, and soybeans) from a farmhouse built by his great-grandfather near Des Moines. He also chairs the Iowa State Commerce Commission (telephone, electric, and gas utility regulation) from fifth-floor offices in a building hard by the gold-domed state capitol.

Varley is relieved that Iowa's electric utility affairs are largely in good order. "It's because," he says, "we've got pretty modern equipment in place—efficient new coal-fired units, also some of the older nuclear units that were built at very reasonable cost and give us cheap energy accordingly." But his Commerce Commission experience has ramifications that quickly cross the state line and draw him into nationwide electricity issues.

A member of the National Association of Regulatory Utility Commissioners since he was named to the Iowa commission in 1979, Varley is now in his third (and final) year as chairman of NARUC's Committee on Electricity. Also as a NARUC member, he was named to EPRI's Advisory Council three years ago and is one of seven regulatory commissioners on that 25-person body.

The Council is a sounding board for EPRI's R&D strategy and plans, a way to elicit opinions from a variety of sources across the nation. The seven regulators themselves have varied backgrounds, and their Council colleagues—who serve staggered terms of four years—bring interest and expertise in such areas as agriculture, business, conservation, education, environmental matters, finance, government, labor, medicine, and science.

These backgrounds reflect several perceptions of what U.S. society needs and wants from its electric utilities. But Varley himself is evidence that such exclusive labels fall short. He can and does think as a farm owner (he has been one for 24 years), as a state legislator (12 years), and as a regulator (5½ years), not to mention as an economist (27 years), family man (25), and Iowan (just a little over 50).

Understandably, it's the economist who shows up most often as Varley talks of his legislative, regulatory, and advisory years. He talks softly and easily, in an organized way that says he is knowledgeable. His voice and manner are not animated, but there is the persistent edge of a smile as he states conclusions, even convictions, without seeming to attach himself to them. Speaking as an economist is comfortable for Varley, who acknowledges that his two colleagues on the Commerce Commission "say I do it all the time. They give me a bad time about it."

Caught up in energy policy

Varley graduated in agricultural economics from Iowa State University in 1957 and added a master's degree at North Carolina State University four years later. Uncertain about "a career in the ivory tower" and anxious for "more direct, hands-on experience," he decided to go back home and run the family's farming interests, which had already

"There is always the example of some commission that denied a segment of a utility's research because the utility couldn't show a current benefit. But that's not the nature of research, certainly not long-range research."

come into his hands. He enjoyed it, he says, but community affairs soon beckoned him; in 1966, caught up principally by an economic issue—rural property taxation for school funding—he ran successfully for the state assembly. "Commodity prices were pretty stable, but property taxes were on a geometric progession," he recalls. "If that didn't change, farmers would eventually become tenants of the state!"

Six terms later, having served as majority leader and speaker of the house, Varley stepped down. School districts were by then drawing more on state income and sales tax revenues, and property tax rates, while not reduced, had been stabilized. "Twelve years is a long time," Varley decided. "Several issues started coming back a second or third time, and they weren't as exciting as the first time."

But one historical event and its aftermath had caught Varley. He was speaker of the house in 1973, when the oil embargo upset distribution patterns for petroleum products everywhere. "We put together a task force of people from various departments of the state government to get on top of the problem. It was essentially volunteer work, with oil companies, brokers, and distributors, and they did a good deal of juggling of fuel supplies. That was the time of gas lines, but we avoided much of that problem in Iowa by building a little flexibility into the system so as to anticipate shortages and get fuel there before they happened."

Varley later helped draft legislation for the permanent Energy Policy Council that encourages conservation and wise use of energy resources in Iowa today. Its appointive membership includes legislators, public members, and a member of the Iowa State Commerce Commission. That last draws a smile from Varley. "Originally, the chairman of the Commerce Commission was the chairman of the council. But we amended the law so that the governor appoints the council chairman. I thought that was a good amendment then, and I still do. Of course, I had no idea that I'd ever be Commerce Commission chairman!"

Exactly that opportunity came only a year after Varley retired from the state legislature, when he was having an enjoyable and successful year as a family man and farmer and, incidentally, serving as one of the public appointees to the Energy Policy Council. Of the Commerce Commission position, he remarks easily, "It's one of the few in state government that would interest me. I had worked on legislation related to the commission, I had a good perception of how it functioned, and with my background in economics I thought the concept of utility regulation was very interesting." The upshot, on less than a week's notice ("I've never had any problems making decisions"), was Varley's appointment to a Commerce Commission vacancy late in 1979, his appointment as commission chairman only three months later, and his appointment in 1983 to a full six-year term. And again he is on the Energy Policy Council, ex officio.

Incentives for R&D

Asked what aspect of regulatory work most consistently catches his interest, Varley readily responds, "New technology. Telephone and other communications hardware is certainly changing dramatically, but electric power technology is fascinating, too—the new kinds of generating units, the size of units, the potential for small increments that can be added as demand develops."

Varley recalls his earliest introduction to a technology that is only now completing development for utility use. "It was at an Iowa State field day when I was a high-school senior in 1951 or '52. They had a little old Allis-Chalmers tractor out there plowing, powered by electric motors with energy from fuel cells that ran on propane. And I thought, 'Boy! this is the technology of the future!'" Varley has been on the lookout for new electric power technology ever since, "even for massive breakthroughs, like we've seen in telecommunications. You might argue that the potential isn't there, but I question that. I suspect there is potential that hasn't been exploited."

This insistent optimism leads Varley to his one reservation about EPRI—that it is not far enough out on the fringe of research, not sufficiently studying concepts and long-range possibilities. "There's been a tendency to concentrate on solving immediate problems, which is fine for the utilities and," he adds candidly, "for the state utility commissioners who like to see some quick payoff." But it could be otherwise, he believes. "I think the leadership of EPRI needs to see a little beyond the day-to-day problems and begin reshaping the direction of the industry 10 or 20 years down the road."

For Varley, the large number of EPRI success stories recounted to the Advisory Council confirms his feeling that the Institute needs to work closer to the edge. "If you're doing meaningful research, you'll have some failures. If everything you try is an overwhelming success, you're not testing anything; you're only practicing what you know."

But don't utilities need immediate R&D success if they are to justify their EPRI memberships? "I've talked about this with the Advisory Council and the EPRI Board," says Varley. "There is always the example of some commission that denied a segment of a utility's research because the utility couldn't show a current benefit. But that's not the nature of research, certainly not long-range research. In most cases I think the regulators are ahead of the Board members in encouraging more investment in R&D—and, in fact, long-range research." Varley returns to the notion of learning from research failures: "The idea that every project should have a demonstrated return really ignores the purpose of research."

Even where R&D success is demonstrable, utilities may be tentative about adopting new technology, and they are often guarded and conservative in their claims for it. They are apprehensive that regulatory bodies may insist on premature exploitation, thereby jeopardizing the economic benefits. Varley responds quickly and emphatically to this notion. "It's something that bothers regulators. We want utilities to be candid with us, but they feel a risk of being penalized if they're candid about developments. When one thing is already in the rate base, they want to wait for it to depreciate before looking at something new."

How to resolve this impasse intrigues Varley and other regulators. "We've talked about figuring out a mechanism for sharing the benefits of innovative practices between ratepayers and stockholders. Then utilities would have a real incentive to go out and do the innovative thing, install the efficient equipment—derive the benefit immediately rather than put it off."

Problems in electricity wheeling

When he discusses the range of relationships and issues between electric utilities and their regulatory agencies, Varley is going well beyond the context of Iowa. Drawing upon his two-plus years as chairman of NARUC's Committee on Electricity, he easily enumerates some of the nationwide concerns: lead times for power plant construction (and the "rate shock" that occurs when a plant's interest-burdened capital cost goes into the rate base), criteria for measuring utility effectiveness (and their unsuitability for comparing one utility with another), wheeling of electricity between utility jurisdictions (and the need to to be aware of technical and institutional impediments).

Wheeling is most current on the committee's agenda. "There are some real problems here," Varley insists, "and I think it's in the industry's interest to address them, no matter how difficult it is, and find a reasonable solution. I don't think the problems will go away if they're ignored."

Utility system interconnections originated for reliability. They have become standing power pools, even regional networks. Although they fall far short of a nationwide grid, there is a formal organization—the North American Electric Reliability Council—to coordinate technical matters. Contractual arrangements are less systematic. Electricity transfers between adjacent utility service territories remain difficult to evaluate for pricing, whether they involve kilowatthours of energy for immediate disaster relief or kilowatts of generating capacity for long-run improvement of reserve margins.

"I think the leadership of EPRI needs to see a little beyond the day-to-day problems and begin reshaping the direction of the industry 10 or 20 years down the road."

But many of today's wheeling proposals have nothing to do with reliability; they are business transactions alone. They pose problems, Varley admits, because of their uncertain mix of institutional and technical factors. He cites several examples.

"For one thing, with traditional wheeling, each utility had virtual veto power over the deal," Varley says. "But buyer and seller may be separated by several utility jurisdictions, even state lines. So commissions are involved, too. The transaction appears to be a windfall for the utilities in the middle. How can it be handled equitably? There really is no pricing mechanism."

Depending on the amount of power involved, however, a wheeling proposal may require extensive investment in new transmission facilities along the route. "But there's no ready system for allocating construction costs," Varley cautions, "and even if there were, it would seem inappropriate to put them into the

"Integrating a nationwide transmission system makes a lot of sense, but what we're lacking is consensus on a pricing system that conveys the proper economic messages to everyone."

rate bases of intervening utilities, whose ratepayers have no stake in the matter." Although he acknowledges that a contract might be worked out for transmission across several service territories, Varley concludes ruefully, "Under our present system there is no guarantee that the people who bear the cost of a line will ever be compensated by the people who benefit from it."

The multijurisdictional problems obviously are considerable. Varley observes that the pattern of overall electricity supply in the United States is one of the most fragmented in existence—at least, among the developed nations. "It's because of the lesser role of the state. Historically, our systems have always been very much geared to individual service territories." In contrast he cites Canada, right next door, where 500 miles of transmission line may be the subject of a single decision by one provincial government agency. "If we were to build 500 miles of power line here, say between Ohio and New England, how many decision points would be involved?" Equitable cost sharing aside, Varley asks, "Who wants a power line going across their state if they aren't getting any benefit from it?"

Varley makes only brief note of the technical problems in wheeling. Stability becomes more difficult, he says, as power inputs proliferate on an already complex network. "One solution could be to build an HVDC line, which is less sensitive. But here again, we don't have the mechanism in place to analyze the need and then make sure it gets built."

Varley knows that the technical issues of wheeling have been discussed by EPRI's Board of Directors. He also realizes that the Board members must consider the best interest of their own service territories. "If they had to authorize research and at the same time agree in advance to go along with all the findings, that would be really difficult for them. The implications aren't technical alone. They're institutional, they're policy, and rather controversial policy." But although Varley can neither see nor control the outcome, he believes it is necessary to move in some fashion. "The controversial issues are the real issues. If they're not controversial, it's generally because no one cares."

Ensuring ratepayer benefits

Benefit to the public, at least to those parties who use and pay for utility services, is one of Varley's guideposts as a regulatory commissioner. The contribution of R&D toward such benefit, and the quality of the connection—these are among the reasons that he and other NARUC members sit on EPRI's Advisory Council.

Because utilities operate in a regulatory environment, EPRI believes that the economic benefits of its R&D assuredly flow through to ratepayers. Varley wholeheartedly agrees. "Ratepayers fund the R&D initially, and then they derive the benefits. When utilities make new investments, they're allowed to get only a fair return. That precludes their extracting any substantial return from newly developed technology."

He also points out that research helps keep utilities viable and that their viability is very much in the interest of stockholders. Varley smiles as he adds, "The only way I can see stockholders deriving exclusive benefit is if research deters a company from a real turkey of an investment! I just don't see a problem. But," he concludes, "I think there is considerable risk to ratepayers from insufficient or inadequate research."

All this is not to say that ratepayers or others of the public are aware of EPRI on a day-to-day basis—or that they need to be. From Varley's experience as a regulator in Iowa, he is resigned to the realization that people don't want to spend a lot of time thinking about how utilities are regulated or how they go about funding research that will provide better service. "They want quality service when they flip the switch," he observes, "and low price when they pay the bill, but without giving it much thought. And I don't know that that needs to change."

Utilities' own awareness of their role is something else entirely. "To the extent that utilities aren't the least-cost source for the service they provide, their customers will look elsewhere," says Varley, adding, "There's nothing that can guarantee a utility's staying in business forever." Again speaking to the need for R&D, he insists that the electric power industry has an obligation to find the improved technology that will help utilities be competitive. "But," he warns, "they may even accidentally find the thing that does them in. That's the hazard that goes with research."

In the course of monitoring EPRI's R&D program, the better to understand its potential benefits to utilities and their customers, members of the Advisory Council are frequently briefed by EPRI technical staff members. Varley remarks that "we do an awful lot more listening than we do advising," but he adds an expectation that this relationship will change. "We're not a bashful group, and one of our suggestions to the Board's Effectiveness Review Task Force last year was that they take more advantage of the Council—probing our thoughts and gaining our perspective of EPRI."

Varley is not calling for more and longer meetings, only for a reallocation of time—"more for input from the Council members, less for telling the EPRI story." To the suggestion that frequent briefings by the EPRI staff give Council members a useful common understanding of utility industry issues and needs, he responds, "The Advisory Council represents diverse points of view. It shouldn't be a surprise to get divergent opinions or differences of opinion."

Economic mechanisms needed

Varley's rural origins and the agricultural context of his education don't set him apart from professional colleagues whose home cities are more populous than the whole state of Iowa. "Economists are economists," he insists. "If the training is good, then it's pretty much the same, whether it is agricultural economics or finance. On the other hand, there are some economists I have a little trouble with!"

Varley feels that many problems of utilities—and of regulatory agencies, too—are a result of getting away from fairly basic economics, "getting wrapped up in current fads of regulation," as he puts it. Price elasticity is a favorite example for this economist. "People do respond to price signals. You can't assume—as many utilities and regulators did in the seventies—that demand will go merrily on, regardless of price. That got a number of utilities into trouble."

Varley's assessment of events after the oil embargo of 1973 is that electricity consumption continued its disproportionate rise (relative to per capita gross national product) largely because of substitution—unit costs of electricity were stable compared with those of petroleum. New power plants were put under construction accordingly, and then, as they came into the rate base, their costs began to send electricity prices up—just when the petroleum market softened and the economy turned down.

"Worse than that," Varley admits, "were some tremendous cost overruns. Utilities couldn't have anticipated the kind of interest payments that would be needed, especially as construction times were strung out." But in Varley's view, too many utilities then consulted their attorneys when they should have consulted their economists. "They indeed had every legal right to recover the inflated plant costs, but that conclusion overlooked the effect of rate shock, a price signal if there ever was one."

Whether electricity consumption is rising slowly or rapidly, whether power plants are large or small, old or new, Varley is content that utilities do all they can on an hourly basis to use the lowest-cost electricity generation—economic dispatch of capacity, as it is called. But, especially as he considers the pressures for wheeling (and its potential), he wonders if the lowest-cost transmission is taking place. "We don't have the mechanisms," he says, "to encourage the most economical overall transactions."

The prospect intrigues Varley. It appeals to his fascination with technology and his loyalty to economics—both of them in service to utility ratepayers. "I'd like to see an integrated transmission grid, with an economic pricing mechanism for moving power on it, so that we could truly make the best use of the generation we have available.

"Integrating a nationwide system makes a lot of sense," Varley goes on, "but what we're lacking is consensus on a pricing system that conveys the proper economic messages to everyone. What we need is a group like the presidential commission on electricity recently proposed by NARUC. It would bring together representatives from NARUC, DOE, private utilities, rural electric cooperatives, municipal utilities, perhaps major users, trying for a consensus solution that would make sense to all the players.

"The real need," he concludes, "is to provide incentives so that utilities want to put together this kind of cooperative venture." If there were such a commission, would Varley serve on it? "Sure," he says, and then he adds thoughtfully, "You know, you wonder if it's too big a problem to solve—at least, too big to conclude in the time an individual could serve. But I think all of us, consumers and the power industry, have a vested interest in getting electricity at the lowest overall cost." ■

"There's no ready system for allocating construction costs [for wheeling] . . . there is no guarantee that the people who bear the cost of a line will ever be compensated by the people who benefit from it."

This article was written by Ralph Whitaker and is based on an interview with Andrew Varley.

Factory-Molded Cable Joints

Pretested, factory-molded joints for 69-kV to 138-kV solid-dielectric cables can be assembled quickly on site to yield connections that are as reliable as the cable itself.

Underground transmission cable is installed wherever terrain, environmental considerations, or development makes the use of overhead line impractical or undesirable. In most such instances, distance precludes a continuous cable run, so sections of cable must be laid or pulled into place and then joined together—spliced. Traditionally, splicing is a delicate and time-consuming process, involving elaborate preparation of the insulation and conductors and requiring extensive training of the splicers.

Only within the past ten years has a new approach—a premolded, factory-tested splice—become available for cables that carry power at transmission voltages. Developed for cable that has an extruded solid dielectric, this and other splicing alternatives were first used in distribution applications.

Techniques and trade-offs

Until 1971, virtually all solid-dielectric cable splices were tape-wrapped on site. This technique calls for shaving the cable insulation into a pencil-like cone, then preparing and splicing the conductor itself, and then carefully wrapping the entire connection. The resulting splice performs well for voltages up to and including 69 kV. But for 138-kV cables (clearly in the transmission voltage range), the tape-wrapped field splice has several drawbacks. It is long (1.5–2.1 m) and up to twice the diameter of the cable. It requires considerable skill and time to perform. Finally, a tape-wrapped splice cannot be pretested to ensure its dielectric strength or to detect voids, which could cause early failure. Many cable failures have been traced to these field-made splices.

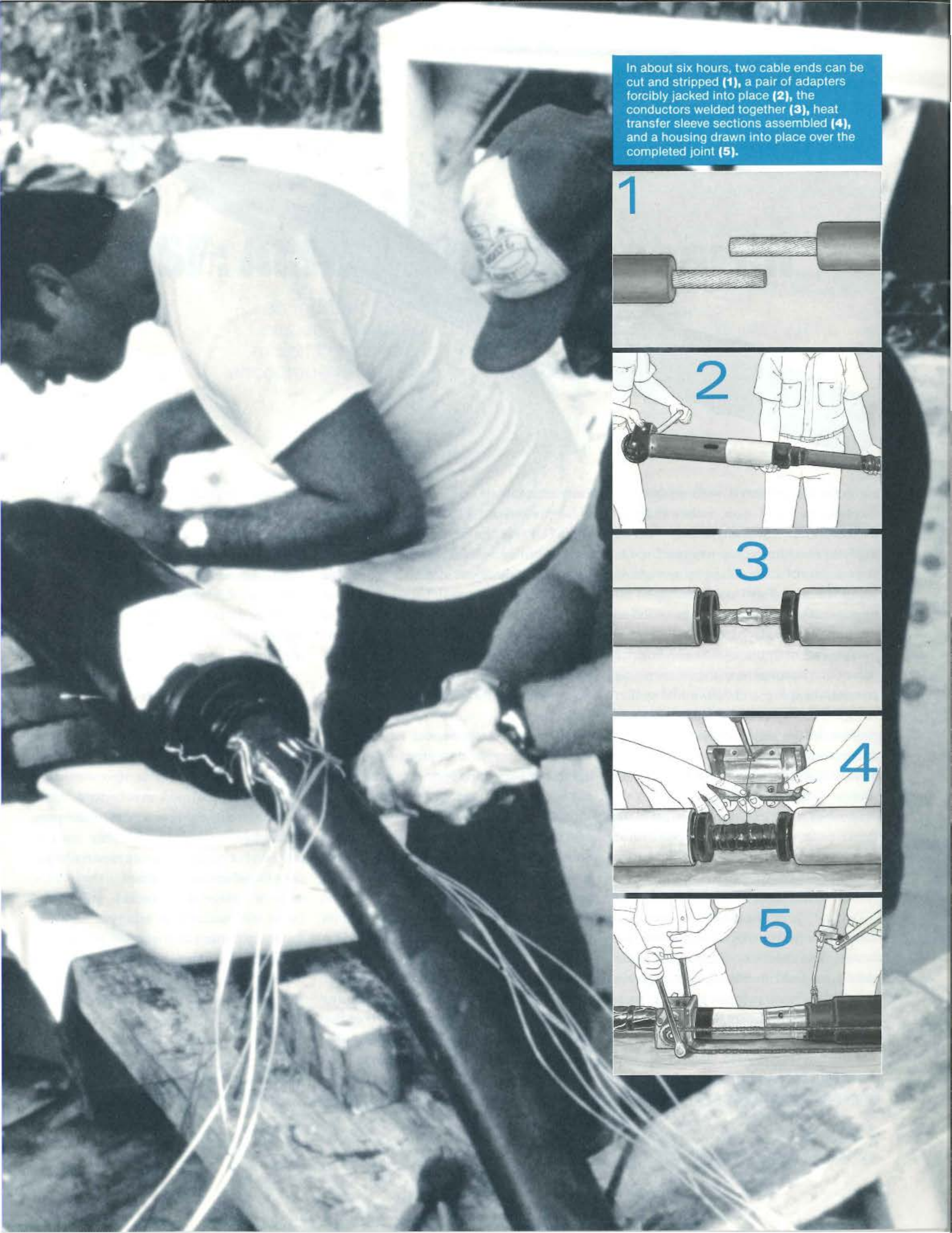
One alternative to the tape-wrapped splice is a field-molded and -cured insulation splice. It eliminates some of the delicate preparation and taping and, when completed, is more compact than the tape-wrapped splice. Field molding has gained considerable acceptance, but it is complicated and also calls for considerable skill. The technique is so sensitive to ambient conditions that it requires portable splicing buildings equipped with air conditioning. Understandably, storage of the chemically reactive splicing compounds is sometimes a problem.

Field-molded splices take 16 to 20 hours (plus curing time) each to install and, like tape-wrapped splices, cannot be pretested for voids or dielectric strength. Clearly, neither alternative offers emergency repair crews much hope of completing a splicing job in the time between daily peak periods on any system.

A second alternative to the wrapped splice is a factory-molded, pretested, slip-on assembly. This accessory was first used successfully on distribution cables with voltages as high as 35 kV. To produce mechanically and electrically sound splice components in the 69–138-kV transmission range, however, the design criteria and the manufacturing processes (including rubber compounding technology, rubber rheology, and injection molding) had to be extended beyond the existing state of the art.

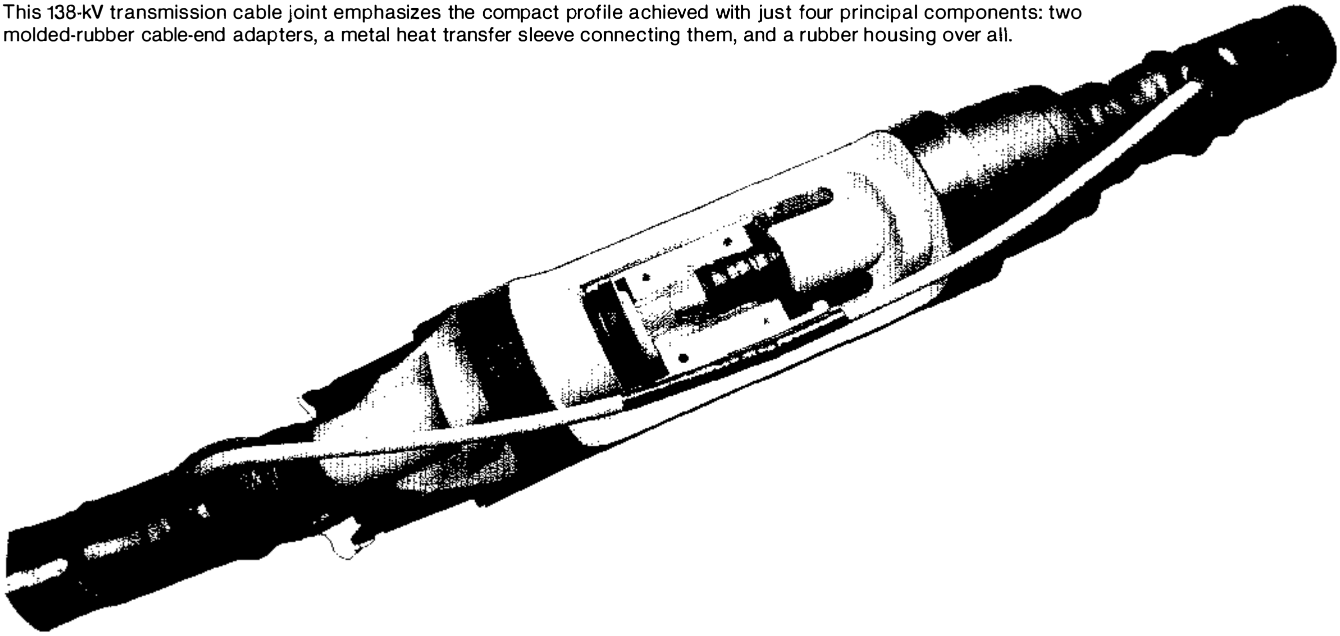
Working under EPRI sponsorship, the Elastimold Division of Amerace Corp. by 1977 successfully developed the first practical premolded, pretested 138-kV splice. Twelve samples thereafter completed a two-year accelerated-life test program at EPRI's Waltz Mill facility with no failures; the accessory, known as a transmission cable joint, is available today. It is a strong, reliable link because of engineering features that, in particular, reduce electrical stress and keep all points in the joint running cooler than the cable conductor.

Installation of the factory-molded transmission cable joint consists of several relatively simple steps. First, the ca-



In about six hours, two cable ends can be cut and stripped **(1),** a pair of adapters forcibly jacked into place **(2),** the conductors welded together **(3),** heat transfer sleeve sections assembled **(4),** and a housing drawn into place over the completed joint **(5).**

This 138-kV transmission cable joint emphasizes the compact profile achieved with just four principal components: two molded-rubber cable-end adapters, a metal heat transfer sleeve connecting them, and a rubber housing over all.



ble ends are prepared with square cuts through the insulation, rather than the difficult and time-consuming "penciling" required for a tape-wrapped splice. Then a pair of cable adapters are added, using an assembly tool developed for this splicing method. After the conductors are joined (by a welding or compression technique), two semicylindrical halves of a heat transfer sleeve are placed around the splice and fastened together. The sleeve also engages circumferential grooves in the adapters and locks them into place. A splice housing is the main insulating barrier; expanded by pumping silicone fluid into it, the housing is slid over the adapters and heat-transfer sleeve to form a very tight, void-free interface. Finally, the cable shield connections are completed—a step that depends on the kind of shielding used.

Two or three workers can complete these assembly steps in about six hours—less than one-third the time required for field molding. Although the premolded joint components are more expensive than the materials for field-molded splices, labor costs are less than one-fifth as high. Also, use of factory-tested joints avoids the necessity and cost of field X-raying.

Early applications

New York State Electric & Gas Corp. (NYSEG) was the first utility to use this factory-molded joint. The application was two 3-phase circuits running 2.3 mi (3.7 km) between substations. Overhead lines were ruled out because of the developed area traversed. The ultimate installation, using two splicing systems, afforded an opportunity to compare factory-premolded and field-molded cable splices.

One of the circuits was fitted exclusively with premolded joints—33 in all. The other was equipped with a combination—10 premolded joints and 23 field-molded splices. Each premolded joint cost nearly $3300 less than a field-molded splice. (NYSEG also estimated that a premolded joint costs $260 less than a comparable tape-wrapped splice.)

About 80 factory-premolded joints have since been installed elsewhere on the NYSEG system. Also, Pennsylvania Power & Light Co. has installed premolded splices in two lines, and Southern Indiana Gas and Electric Co. is in the process of adding them to its inventory of underground cable accessories.

According to Elastimold's production manager, Vincent Boliver, markets for the factory-molded splices are particularly promising abroad, where solid-dielectric (rather than oil-filled) cable in the 69–138-kV range is used extensively. Utilities in some nations are building entire new solid-dielectric cable systems, whereas most U.S. utilities are only adding piecemeal to existing underground transmission.

The factory-molded joint provides several advantages over other methods for splicing solid-dielectric transmission cable. Clearly, ease and speed of installation yield a direct saving of time and money. Less training is necessary for installation personnel, and because components are tested in the factory, the premolded joint provides a highly consistent level of quality. Quality is perhaps its greatest advantage, realized in the avoidance of outage costs, which are sometimes reckoned at $1 per day per kilowatt just for rerouting or importing power lost by the failure of a cable splice.

This article was written by Stephen Tracy, science writer. Technical background information was provided by Felipe Garcia, Electrical Systems Division.

NSF: Aiding Basic Research

As an independent federal agency, the National Science Foundation (NSF) annually provides millions of dollars in grants and contracts to encourage research in science and engineering.

Typically, federal agencies in Washington, D.C., are applications oriented, allocating research funds to achieve specific goals and results. NSF, however, is different. This science agency, created by Congress in 1950, is concerned solely with promoting basic research in a wide range of scientific and engineering fields. Although it funds relatively few projects directly related to power systems, NSF's contributions to basic engineering and atmospheric chemistry research may help utilities improve the design and operation of their systems and increase their understanding of emissions transport.

Each year, NSF awards funds to more than 2000 colleges, universities, and other institutions conducting research. The largest portion goes to college and university programs, with NSF grants representing about 28% of the federal funds academic institutions receive for basic research. Also receiving NSF financial support are other nonprofit institutions and small businesses. In addition to individual research projects, NSF funds cooperative efforts between industry and academia and between the United States and other countries. The NSF budget for fiscal year 1985 totalled $1.5 billion, including $1.3 billion for research and related activities and $82 million for science and engineering education.

NSF policy is set by the National Science Board, a panel of 24 members appointed by the president and confirmed by Congress. Board members, who serve six-year terms, include college and university professors and industrial scientists and researchers. The present chairman, Roland Schmitt, is senior vice president for corporate research and development of General Electric Co.

The board is also responsible for approving all NSF grants of more than $500,000 a year. Because it wants more time to review a wider range of NSF programs and to focus on national science policy, however, the board has recently asked Congress for permission to delegate its funding approval authority to the NSF director. Erich Bloch, a former vice president of IBM, is currently serving in that position. Bloch, like his deputy director and four assistant directors, is also appointed by the president.

Once NSF policy is set, it is carried out by 1200 staff members who work in areas, called directorates, that were created along the lines of academic disciplines. The agency has seven directorates in all: astronomical, atmospheric, earth, and ocean sciences; biological, behavioral, and social sciences; engineering; mathematical and physical sciences; scientific, technological, and international affairs; science and engineering education; and administration.

About one-third to one-half of the personnel directly responsible for proposal selection are on one- or two-year loan from colleges and universities around the nation. This policy ensures that inhouse staff are knowledgeable about the latest developments in their fields.

More than 27,000 unsolicited proposals are sent to NSF each year. Although NSF staff members make the final decisions regarding proposal funding, they do solicit input from members of the scientific community in the form of peer review. More than 50,000 scientists, engineers, and researchers participate in NSF activities each year, either as proposal reviewers or as members of advisory panels.

Engineering Research

NSF funding for projects directly related to power plants and systems is provided through the Directorate of Engineering. Engineering's budget of $150 million for FY 1985 is considerably smaller than the budgets of other directorates, reflecting the agency's traditional focus on the physical and social sciences. Of that amount, no more than $300,000 is devoted to projects directly related to the electric utility industry. Other engineering projects, however, are exploring important areas that are of interest and concern to utilities.

The engineering directorate's division of electrical, communications, and systems engineering furnishes funding for power system research. The majority of these funds are used for research related to the stability of large, interconnected power systems. Some funding also goes to investigate potential techniques for fault detection and prevention.

Michael Polis, who directs the division program that receives the most proposals for power system research, notes that the relatively modest amount of money for such research does not reflect the quality of the proposals but rather the lack of additional funds. "I'm faced with the problem of receiving a number of proposals on power systems, being able to take maybe half a dozen that I consider fundable, and having only enough money for one, possibly two, of them."


Polis

Blake Cherrington, director of the electrical, communications, and systems engineering division, explains that the engineering directorate is considering establishing a separate program within his division to increase support for power system research. Meanwhile, he notes, "We're concerned with at least keeping some reasonable level of support going in the thrust of what we're doing this year."

In addition to funding specific power system proposals, NSF has provided grants to two power system researchers who were chosen as winners of the agency's Presidential Young Investigator awards. Each—Vijay Vittal of Iowa State University of Science and Technology and Marija Ilic-Spong of the University of Illinois—will receive up to $100,000 annually for five years, including a basic NSF grant of $25,000 per year and up to $37,000 in additional NSF funds annually to match private sector contributions. The program's goals are twofold: to help universities attract and retain scholars early in their careers by providing adequate support for their research and to introduce these young people to industrial issues and problems. In the 1984 competition, NSF selected 200 award winners out of more than 1000 applicants.

Cherrington points out that many of the fundamental ideas being developed in other engineering areas, while not directly related to power systems, can be applied to utility problems. For example, NSF is financing research into potential methods for designing large structures that can withstand severe conditions such as earthquakes. This kind of work explores the same issues that utilities consider in building power plants. Also, Cherrington explains, NSF supports a considerable amount of research to develop computer control systems that could be utilized by large users—such as utilities—to monitor and control power systems.

Other applicable research focuses on developing optical instrumentation systems, advancing the knowledge of sensing and measuring instruments, designing low-environmental-impact structures and improving the overall design process, and understanding high-voltage research. Regarding programs that address large network problems, Program Director Polis comments, "This research has relevance whether one is interested in power systems, in scheduling vehicles, or in a wide range of other applications. The methods are basically the same; however, the specific implementations will differ because of the physical constraints, so we're developing a variety of techniques."

As an example of an NSF-funded project applicable to utilities, Polis cites a package that was designed by a Stanford University scientist to solve linear programming problems. "That type of research is normally considered under optimization or operations research," he explains. "But, on the other hand, it's now part of a commercial package that is evidently quite popular with the utility companies for calculating their load flow."

Reorganization

Following a 1983 National Science Board directive that it change and expand its engineering research and educational activities, NSF is showing signs that it may step up its emphasis on engineering. The agency is proposing a 13% increase in the engineering directorate's budget for the 1986 fiscal year. This change would raise the directorate's budget to $170 million. By comparison, NSF as a whole is seeking an increase of only 4.4%, which includes a 7% increase in research funds.

Another sign of its heightened emphasis on engineering is NSF's recent reorganization of programs within the engineering directorate. This program restructuring has created a number of new divisions composed of related research areas and has eliminated old divisions that were generally related to engineering specialty fields. One new division—emerging and critical engineering systems—will examine such promising new fields as light-wave technology, bioengineering, and biotechnology, as well as other crucial areas like earthquake and environmental engineering and toxic waste hazards mitigation. The directorate's four other new divisions are chemical, biochemical, and thermal engineering; mechanics, structures, and materials engineering; electrical, communications, and systems engineering; and design, manufacturing, and computer engineering. Also established is a new office of cross-disciplinary research.

NSF hopes that the reorganization will bring a better balance to emerging and established engineering disciplines and that it will increase links between academic and industrial engineering. The agency also hopes, adds Cherrington, that this restructuring will foster the development of programs that will address areas of tremendous need and potential, thereby helping the directorate make a good case to Congress for additional funding. "We realize that we can't do everything we'd like to do; however, we're committed engineers. We feel that the needs out there are absolutely staggering, but being politically realistic, we know we're not going to [reach our goals] for a long time in terms of our budget growth."

Cherrington

Still another indication of the priority being given to engineering is a major new initiative launched by the engineering directorate to establish multidisciplinary engineering centers at a number of universities. Twenty-five million dollars of the proposed $170 million engineering budget is earmarked for these centers. The first, to be established in the near future, is to be followed by as many as 10 more during this year alone. The goal for the next five years—as recommended by a panel of the National Academy of Engineering—is 25 centers. Each would conduct research that is not currently feasible in a university setting. Such a program would thus expand the scope of academic engineering and provide increased engineering and training opportunities.

Under the plan, private industry will provide a substantial portion of the funds required for the centers, increasing academic and industrial collaboration in furthering knowledge. Cherrington explains that universities simply do not have the resources to tackle large-scale engineering problems. The centers, he said, will provide the resources needed to conduct "large-problem kinds of research activities within the university structure."

Atmospheric Chemistry Research

Although NSF's engineering directorate is the primary sponsor of projects directly related to power plants and systems, other research of interest to electric utilities is being funded through NSF's atmospheric chemistry program, which is in the directorate for astronomical, atmospheric, earth, and ocean sciences. With a budget of $6.9 million for FY 1985, the program is providing funds for about 90 projects that are aimed at developing a fundamental understanding of the atmosphere's chemistry rather than at addressing specific problems and issues. "I look at our program in atmospheric chemistry as really cutting across the various issues," explains its director, Jarvis Moyers. "We really are trying to look at it from a discipline point of view."

Nevertheless, Moyers notes that many of the projects supported by the program have direct or indirect bearing on issues such as acid rain or regional-scale pollution. For example, Moyers cites an NSF-funded project in which a scientist, Barry Huebert of Colorado College, has conducted dry deposition measurements of nitric acid. Using his own techniques, Huebert has conducted research studies both in problem areas and in clean, remote areas. Such projects, explains Moyers, help provide answers about how the natural atmosphere operates and, at the same time, provide information about current areas of concern.

Moyers says there is a relative lack of knowledge about the atmosphere's chemistry because the field is relatively new—no more than 25 years old—and because it has concentrated on specific problems, beginning with urban air pollution. "The whole field has been driven by the 'problem of the day' or the 'problem of the decade,'" he comments. "There's never been a detailed look at the whole system—the atmosphere as a whole."

Moyers

About two-thirds of the atmospheric chemistry program's financial support goes toward studies of the lower atmosphere (the troposphere) and one-third goes toward studies of the middle atmosphere (the stratosphere). A small percentage is used for research on the upper atmosphere. The program's overall emphasis on the atmosphere's chemistry "really includes going all the way from laboratory studies to field measurements to modeling the process involved in defining the chemistry," Moyers says.

A substantial portion—about 30%—of the NSF funding is used by researchers to develop instruments and techniques for measuring and observing the atmosphere. This endeavor includes not only developing instruments for taking accurate measurements, such as laser-based remote sensing systems, but also optimizing the performance of more traditional measurements so they can be used in the field.

Another third of the funding is used for actually taking atmospheric measurements to examine the atmosphere's photochemistry and the biochemical cycles of elements through the atmosphere. About 25% of the money funds laboratory studies of atomic and molecular atmospheric processes, with the remaining 15% devoted to modeling efforts aimed at simulating what is occurring in the atmosphere.

Moyers comments that the general flavor of the program is determined largely by members of the scientific community who submit the proposals that are reviewed by NSF. "We try to pick those projects that are going to be the best science, regardless of whether they are directed toward stratospheric or tropospheric chemistry." In the peer review process, a program manager sends each proposal to four to seven experts in the field. They are asked to comment on the proposal's scientific worthiness and its appropriateness for NSF funding. On the basis of the reviewers' recommendations and the funds available, NSF then determines whether to provide the proposal with support.

In the future, Moyers expects the atmospheric chemistry program to become more involved in the kinds of large-scale, organized research recommended last fall by a panel of the National Research Foundation. NSF and the National Aeronautics and Space Administration asked the panel to assess the current state of knowledge concerning tropospheric chemistry and to prepare a plan for a global study. The panel's report, entitled "Global Tropospheric Chemistry: A Plan for Action," cited a lack of knowledge concerning fundamental processes and recommended that the United States serve as leader in launching a major international research effort. The report, according to Moyers, essentially said, "Let's look at the fundamental processes that are occurring and what controls atmospheric composition, and then we will be in a much better position to respond to existing problems as well as those that are undoubtedly going to show up in the future."

To continue its work, NSF asked for a $66.7 million increase in its FY 1986 budget, raising the total budget to $1.57 billion. NSF Director Erich Bloch, in a statement issued by the agency, said the proposed budget "continues the positive momentum in science and engineering provided by the administration and Congress over the past several years." As NSF continues its work in the years ahead, no doubt utilities—and the nation as a whole—will continue to reap the benefits of increased knowledge in the sciences and engineering. ■

This article was written by Doris Newcomb, a free-lance writer specializing in energy issues.

EPRI Direction Set for 1986

In addition to approving an overall budget for 1986, EPRI's Board voted to continue funding a broad spectrum of research projects and approved funds for two new pilot plant/demonstration projects.

At its April 9 meeting in Washington, D.C., EPRI's Board of Directors established the 1986 payment formula for member utilities and approved an overall budget for 1986 of $363 million, $294 million of which is earmarked for research and development.

In the first of two major cofunding actions, the Board approved a $25 million commitment to the design, construction, and operation of the Shell Coal Gasification Pilot Plant (SCGP-1) at Shell Oil Co.'s Deer Park manufacturing complex in Texas (RP2695).

A joint project with Shell Oil Co. and Lummus Crest, Inc., the pilot plant will produce clean, medium-Btu gas by using the Shell coal gasification process; this process incorporates a dry-coal feed system to fuel an entrained slagging gasification reactor that operates under elevated pressure. The plant is expected to provide all the design, operating, environmental, and economic information needed for a successful scale-up of the technology to commercial-size plants.

The facility is being engineered by Lummus Crest's Bloomfield Division. Shell Development Co., a division of Shell Oil, will operate the plant. Construction is expected to begin later this year, with startup planned for early 1987. The estimated total cost of the project, including a two-year test program, cannot be predicted with certainty until final construction bids are received later this year.

Commenting on the Board action, Dwain Spencer, EPRI vice president and director of the Advanced Power Systems Division, said, "The Shell pilot plant will provide the ability to handle a wider variety of coals and expand the gasification technology base available to the electric utility industry. Shell's gasification process promises a low-cost, environmentally sound way to convert nearly any coal into medium-Btu gas that can be burned to generate electric power."

In its second major cofunding action, the Board voted to participate in building a circulating fluidized-bed combustion (FBC) boiler demonstration plant (RP-2683) at the Nucla generating station, owned by Colorado-Ute Electric Association, Inc., of Montrose, Colorado. The project is intended to demonstrate the technical, economic, and environmental performance of a 110-MW circulating atmospheric FBC boiler. EPRI will contribute toward the estimated $114 million cost of the project.

A number of other research projects received Board attention. Funding for the hot gas cleanup project to develop a commercial high-temperature, high-pressure gas filter for turbocharged pressurized FBC boilers (RP1336) was increased, as was funding for the performance improvement and monitoring project to enhance boiler, turbine, and balance-of-plant efficiency in fossil fuel plants (RP1681 and RP2153).

Funding increases were awarded to an alkali scrubbing chemistry project (RP-1031) and a project dealing with the operation and control of cycling fossil fuel plants (RP1184). Additional funding was approved to continue work in closed-cycle water chemistry control (RP1261).

The Board accepted in principle General Electric Co.'s donation of its High-Voltage Transmission Research Facility and approved an increase in funding for a transmission research project at the facility (RP2472). The Board also approved extending the lease of the Waltz Mill Underground Cable Test Facility for two and a half years (RP7801) and authorized additional expenditures toward continued development of the amorphous metal power transformer (RP2236).

Article Series on Fabric Filter Technology

In 1975 EPRI initiated a fabric filter research program that included laboratory, pilot, and field studies of baghouses in utility applications. A series of articles, published in the *Journal of the Air Pollution Control Association* from January to June of 1984 and written by EPRI's Robert Carr and Southern Research Institute's Wallace Smith, detailed the findings of that program, discussing the performance of baghouses in the utility industry and the unresolved issues in baghouse design and operation. The six articles have now been assembled under one cover and are available through the Research Reports Center (CS-3724-SR).

The first two articles provide basic information on baghouse design and operation, as well as a history of fabric filter technology and its evolution within the U.S. electric utility industry. The third examines a number of design and operation characteristics that govern baghouse performance. For example, it has been found that fabric selection can influence the formation of dustcakes on the bags, now thought to be the single most critical factor relating to baghouse performance. Also, bag life—which can have a major impact on plant operating and maintenance costs—is strongly affected by the fabric and finish of the bag, the quality control measures used in manufacturing the bag, and the methods used in cleaning the bag. The article also discusses the influence on plant capital and operating costs of the two fundamental baghouse design and operating parameters, air-to-cloth ratio and pressure drop.

Other articles cover plant performance data, studies of dustcake properties, and the impact that various bag-cleaning methods have on bag life and dustcake formation. The concluding article summarizes ongoing and future baghouse research, development, and demonstration. It examines two commercially available technologies that combine SO_2 control with baghouse particulate collection—spray drying and all-dry sorbent injection. Because they offer a simple, low-cost replacement for traditional wet scrubbers, both are receiving intensive utility attention. In fact, Public Service Co. of Colorado has already demonstrated the viability of dry sorbent injection using sodium reagents at its 22-MW Cameo Unit 1, where 70% SO_2 removal was confirmed. The company recently committed itself to the technology on a new, 500-MW unit scheduled to begin service in 1990.

Since baghouses were first installed by a utility over a decade ago, they have proved to be an economical and environmentally sound emissions control technology. Their impressive record of controlling total particulates and fine-particulate matter will be further enhanced by the use of advanced fabrics, better bag-cleaning methods, and the combined SO_2–particulate control options. The newest generation baghouses, which range in size up to 800 MW, have incorporated many improvements in flue gas flow distribution, component design, and bag fabric. The research described in this series of articles promises to identify additional advances that will help improve baghouse performance and increase the use of baghouses by the utility industry.

Cool Water Project Wins Environmental Award

The Cool Water coal gasification plant was recently awarded *Power* magazine's 1985 Environmental Protection Award. The award, now in its 15th year, is granted by the magazine's board of directors to those companies that have taken a leadership role in protecting our nation's air and water.

A plaque was presented to EPRI Vice President Dwain Spencer, Advanced Power Systems Division, during ceremonies at the American Power Conference in Chicago on April 22.

The award is given to foster continuing technical solutions to today's environmental problems. Recipients are chosen by the magazine's editorial board, which studies plants throughout the country, identifying those community-minded, pace-setting facilities that represent environmental leadership.

Cool Water is the nation's first commercial-scale plant to use the integrated gasification–combined-cycle technology to generate electricity while minimizing air, water, and solid effluents. It is designed to convert up to 1000 tons of coal a day into a clean-burning synthesis gas. Burning this gas in a General Electric Co. combined-cycle generating unit produces approximately 100 MW (net) of electricity.

In addition to EPRI, which provided key engineering and financial support to the project, other Cool Water project participants include Texaco Inc., Southern California Edison Co., Bechtel Power Corp., General Electric Co., and the Japan Cool Water Project Partnership.

Empire State Electric Energy Research Corp. (a consortium of New York State utilities) and Sohio Alternate Energy Development Co. also contributed to the program.

Another important aspect of the Cool Water project is the price support guarantee from U.S. Synthetic Fuels Corp. SFC is committed to helping cover the cost of producing syngas at the plant during the first five years of operation if plant revenues from electricity sales cannot meet operating and maintenance expenses. ■

Lighting Research Undertaken With NYERDA

EPRI and the New York State Energy Research and Development Authority recently agreed to cofund innovative lighting and daylighting research. The research is expected to benefit architects, designers, manufacturers of window products, and others concerned with efficient, cost-effective lighting.

The initial effort will be a two-year project that will first investigate energy-use implications of various window, door, and skylight designs and treatments and then will develop standardized testing and calculating procedures.

"As architects add daylighting to building design, they tend to focus on increasing the lighting level without considering the heat transmitted and the added cost of air conditioning to make the building comfortable," says EPRI project manager Stephen Pertusiello.

The research will investigate performance characteristics, such as energy use, peak demand, and glare. Also, according to Pertusiello, "Standardized lighting and heating performance indexes for building designers and window manufacturers will be developed."

A technical advisory committee—composed of representatives from the American Institute of Architects; the Illuminating Engineering Society of North America; the American Society of Heating, Refrigeration, and Air Conditioning Engineers; the Department of Energy; the National Fenestration Council; and other similar organizations—will give advice during the study.

The Energy Authority is a public benefit corporation created by the New York state legislature in 1975. It is responsible for fostering safe, dependable, renewable, and economic energy sources and conservation technologies. EPRI and the Energy Authority will periodically announce additional joint projects on a range of energy-related subjects. ■

CALENDAR

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

JUNE

4–5
EPRI Coal-Water-Slurry Project Review
Hartford, Connecticut
Contact: Craig Derbidge (415) 855-2427

4–6
Artificial Intelligence Application to Nuclear Power
Palo Alto, California
Contact: David Cain (415) 855-2112
or Bill Sun (415) 855-2119

4–7
9th FGD Symposium
Cincinnati, Ohio
Contact: Stuart Dalton (415) 855-2467

10–14
Seminar: Electrical Design of Transmission Lines
Lenox, Massachusetts
Contact: John Dunlap (415) 855-2305

11–13
Symposium: Fossil Fuel Plant Cycle Water Chemistry
Atlanta, Georgia
Contact: Roland Coit (415) 855-2220
or Barry Dooley (415) 855-2458

18–21
Symposium: Condenser Biofouling Control
Orlando, Florida
Contact: Winston Chow (415) 855-2868

19–20
Workshop: Fuel Oil Utilization
Atlanta, Georgia
Contact: William Rovesti (415) 855-2519

24–28
Seminar: Electrical Design of Transmission Lines
Lenox, Massachusetts
Contact: John Dunlap (415) 855-2305

26–27
Seminar: Maintaining Equipment Qualification
Palo Alto, California
Contact: Robert Kubik (415) 855-8905

JULY

9–11
Annual Review of Demand and Conservation Program
San Diego, California
Contact: Joseph Wharton (415) 855-2924

SEPTEMBER

9–11
International Symposium: Gas-Insulated Substations
Toronto, Canada
Contact: Vasu Tahiliani (415) 855-2315

17–19
3d Symposium: Integrated Environmental Control
Pittsburgh, Pennsylvania
Contact: Edward Cichanowicz
(415) 855-2374

OCTOBER

8–10
Seminar: Fuel Supply
San Antonio, Texas
Contact: Howard Mueller (415) 855-2745

Test Facility Lowers Underground Cable Cost

The EPRI Cable Test Facility at Waltz Mill, Pennsylvania, has become the focal point for electric power industry research on high-voltage underground transmission lines, as well as a source of reliable information on cable design for individual utilities. Duquesne Light Co. relied on information from field tests conducted at the facility when ordering a new cable with reduced insulation thickness for its underground transmission system. Installation, operation, and accelerated-life testing at Waltz Mill demonstrated the reliability of the new cable, which was developed using previous EPRI research to improve cable design, material quality, and manufacturing techniques. By using the reduced-insulation cable, Duquesne Light estimates an overall saving of $481,000 in capital and carrying costs over a 10-year period. In addition, the thinner cables proved easier to install and require fewer splices in a total line. ■ *EPRI Contact: John Shimshock at Waltz Mill (412) 722-5781*

New FGD Duct Liners Save LADWP $17 Million

The duct liners in some flue gas desulfurization systems must sometimes be repaired or replaced because of severe corrosion after only six months, rather than during normally scheduled maintenance shutdowns. To avoid such a premature outage at its new Intermountain Power Project, Los Angeles Dept. of Water & Power (LADWP) used the results of an EPRI materials evaluation program. A task force observed several duct materials being tested by Battelle, Columbus Laboratories at the R. D. Morrow, Sr., Power Plant of South Mississippi Electric Power Association. The tests confirmed that the material LADWP selected should perform well during the 12 to 18 months between normal shutdowns. The utility estimates a $17 million savings by avoiding premature unit outage. ■ *EPRI Contact: Charles Dene (415) 855-2425*

CAD Software Optimizes PSPL's Relay Settings

To help utility engineers select and set protective relays without the need for cumbersome, error-prone hand calculations, electrical engineers at the University of Washington developed a computer-aided design (CAD) software package that can do the job. Developed under EPRI sponsorship, with the participation of Puget Sound Power & Light Co. (PSPL), this analytic tool optimizes relay settings for a transmission and distribution system after conditions have changed enough to alter fault currents. Tests on the PSPL system showed that the CAD software yields settings that are equal to or better than those obtained from laborious hand calculations, while promising to save the utility at least three worker-years annually on the part of the protection engineering staff. ■ *EPRI Contact: James Mitsche (415) 855-2298*

Boston Edison Uses SIMULATE to Cut Costs and Boost Fuel Use

Boston Edison Co. frequently has to bring its Pilgrim nuclear plant to 50% power during summer months to do condenser backwashing. Utility engineers needed an analytic tool to guide and optimize escalation back to full power in order to improve fuel usage. Boston Edison found that the necessary calculations could be performed using SIMULATE, an EPRI code that can also be used for core design and reload safety analysis. On the basis of calculations performed with the code, power escalation time at Pilgrim was cut significantly, and the utility also expects to be able to save up to eight fuel bundles per reload by using SIMULATE for fuel management. As a result, Boston Edison anticipates saving $6 million in replacement power costs and fuel savings over the next five years. ■ *EPRI Contact: Walter Eich (415) 855-2090*

GO Code Helps SDG&E Make Availability Decisions

Like other utilities, San Diego Gas & Electric Co. (SDG&E) needed a more-efficient, yet low-cost, way of analyzing system availability than the traditional block diagram method. The answer: a computerized methodology called GO that can help utilities perform complex system reliability/availability analysis. Developed under EPRI contract, the GO method employs straightforward inductive logic to model system performance, accounting for both success and failure states. Further, GO can model a system to resemble its engineering schematic, making it easier for designers and engineers to learn its analysis logic. As a result of the technology transfer effort, over 30 nuclear utilities have in-house capabilities to apply GO methods, and a GO users group has been organized. In addition, there are over 10 utilities that routinely use GO techniques to analyze their plant-specific systems. For example, SDG&E has used GO availability input to make a variety of decisions affecting plant fuel oil supply systems, natural gas compressor stations, and the design of a new binary-cycle geothermal plant. As a result, the utility estimates that the GO program has saved it $220,000 on a one-time basis. ■ *EPRI Contact: Boyer Chu (415) 855-2111*

Frozen-Water Vests Keep TMI-2 Workers Cool and Safe

The clothing maintenance workers must wear for radiation protection in nuclear plant buildings impairs air circulation and evaporative cooling. As a result, a worker may experience heat stress and may have to leave the work area after only a short period. In fact, when GPU–Nuclear began the TMI-2 cleanup in 1980, heat stress, not radiation exposure, was found to be the limiting factor for work time. GPU needed a way to extend worker hours without impairing health. In response, Pennsylvania State University, under EPRI contract, designed a vest containing small packets of ice that is worn under the radiation garments, cooling the worker as he or she works. The vest proved successful in lowering heart rate and body temperature without restricting mobility or flexibility. GPU has over 1100 frozen-water vests in use at TMI-2 and reports it is saving money by reducing the risk of heat-related illness and doubling safe work time. Frozen-water vests are also in use at several other utilities. ■ *EPRI Contact: John O'Brien (415) 855-2214*

TVA Evaluates Customer Demand With HELM Code

Used by TVA since 1982 as a key tool for evaluating demand-side management programs—including conservation and load-management efforts—the hourly electric load model (HELM) is now available for industrywide use through the Electric Power Software Center. HELM was developed under EPRI contract to respond to increasing utility activity in end-use forecasting and demand-side management. Sophisticated and effective—HELM saves TVA an estimated $146,000 a year—the model is able to combine hourly load shapes at end-use levels with customer/rate classes. HELM assumes a "business as usual" approach and adds "what if" simulations to ultimately project the impact of new electricity-using technologies, demand-side management, and weather on utility load curves. In addition to TVA, 34 other utilities are using the model, which can flexibly accommodate differences in the amount and detail of required input and yields utility-specific data in the form of tables and plots. ■ *EPRI Contact: Ahmad Faruqui (415) 855-2630*

Nevada Utility Integrates Demand Forecasting Models

Sierra Pacific Power Co. (SPPC) was recently faced with a tough new regulatory problem—producing well-documented end-use demand forecasts for its Nevada service area for the next 20 years. The utility solved its problem by selecting some of the most advanced end-use models available, including several developed under EPRI auspices, and integrating them to produce an overall demand forecast. SPPC used three EPRI-sponsored models—the REEPS model for residential projections, the COMMEND commercial forecasting model, and the HELM hourly load model—to help combine the various sector forecasts. By building on this software, SPPC was able to concentrate efforts on the aspects it knew best, tailoring the models to local conditions. Sierra Pacific officials say the utility saved $125,000 by using the EPRI models instead of going to consultants or buying commercially available computer models. ■ *EPRI Contact: Clark Gellings (415) 855-2610*

Licensed Kinetic Bonding Technique Is Faster, Stronger

Foster Wheeler Energy Corp. has licensed a kinetic bonding method to improve tube sheet welding and is making the technique available to customers. Developed by EPRI, this technology enhances the quality of welds between condenser tubes and their supporting tube sheets and reduces the possibility of tube sheet damage. The kinetic bonding technique involves inserting a small explosive charge into the end of each tube, where it fits into a hole of its tube sheet. The explosive is ignited, forcing the pieces of metal together with such velocity that their surfaces become permanently bonded. In the EPRI version of this technique, each explosive charge is contained in a plastic plug that distributes the force of the explosion to create a welded bond far stronger and more leak resistant than that created by conventional fusion welding. Hundreds of these plugs can be ignited in a single firing, offering significant savings in labor time over standard welding, which must be done tube by tube. ■ *EPRI Contact: Wylie Childs (415) 855-2058*

R&D Status Report
ADVANCED POWER SYSTEMS DIVISION

Dwain Spencer, Vice President

DEWATERING LOW-RANK COALS FOR SLURRY-FED GASIFICATION

Gasification processes based on slurry-fed reactors are an important option for future plants for converting coal cleanly and efficiently to electric power. This is exemplified by the recent successful operation of the Cool Water gasification–combined-cycle demonstration plant, which uses the slurry-fed Texaco gasifier. Thermal dewatering processes offer the prospect of highly concentrated coal-water slurries for improved performance of low-rank coals (LRCs) in slurry-fed entrained-flow gasifiers. The development of a technically effective and cost-effective dewatering process could, therefore, greatly extend the range of coal feedstocks suitable for gasification-based power plants that use slurry technology to introduce coal into the gasification reactor.

LRCs are generally characterized by a high level of chemically bound moisture, which affects their use in water slurries. Together, this inherent moisture and the additional water required to make a pumpable slurry result in excess water and a rather low solids concentration. Such excess water in the slurry feedstream to an entrained gasifier requires more oxygen to provide energy for evaporation, thereby lowering reactor efficiency. Thus an irreversible process for dewatering coal (i.e., one that prevents the reabsorption of moisture) could upgrade LRC as a fuel for electric power generation (EPRI CS-1768).

Various techniques for drying LRC have been explored, including hot air, steam, and hot water techniques. Drying by direct exposure to hot gases has its drawbacks: not only does it result in shrinkage, dust, and fire hazards, but the dried product soon reabsorbs moisture to its original equilibrium level. In the 1920s Fleissner developed a semibatch steam drying process. More recently, however, interest has focused on the development of a continuous, nonevaporative, high-pressure dewatering process—hot water drying. DOE, for example, is sponsoring a project to build a hot water drying pilot plant at the University of North Dakota's Energy Research Center.

EPRI is sponsoring related work to evaluate the technical feasibility of producing free-flowing (i.e., pumpable) LRC-water slurries with a high solids loading and energy content suitable for slurry-fed entrained-flow gasifiers. Under RP2470-1 an experimental study at the Energy Research Center has explored several process alternatives for drying LRCs.

Project approach

The study involved the thermal dewatering of three LRCs by two commercial hot air drying methods and by contact with steam or hot water under pressure in bench-scale autoclave experiments. Hot water drying was also performed in a small, 10-lb/h (1.26-g/s) continuous process unit to prepare larger quantities for slurry rheology tests. After drying, the coals were either blended with water or concentrated from a dilute condition to determine maximum solids loading for a pumpable slurry. The viscosity of the LRC-water slurries was then measured at various concentrations.

The LRCs studied were a North Dakota lignite from the Indian Head mine, a Texas lignite from the Martin Lake mine, and a Wyoming subbituminous coal from the Black Thunder mine. Samples of high-volatile eastern bituminous coal from the Illinois No. 6 River King mine and the Pittsburgh No. 8 Shoemaker mine were used for rheological comparison only.

The two hot air drying processes served as a baseline for evaluating steam and hot water drying. For both hot air processes, the three LRCs were ground to a particle size of 7 mm × 0 (¼ in × 0). In one treatment, the LRCs were dried with hot air in a rotolouvre drier at feed rates and temperatures yielding a final moisture content of approximately 15 wt%. In the other treatment, the LRCs were dried with hot combustion gases in a Parry turbulent entrainment drier at the Colorado School of Mines. The final moisture content of these samples was reduced to less than 5 wt%.

For steam drying, the three LRCs were ground to a particle size of 10 × 7 mm (⅜ × ¼ in) and were subjected to nominal process temperatures of 270, 300, and 330°C. Hot water drying experiments were conducted at similar temperatures and used two grind sizes—a coarse grind (75 wt% of the particles larger than 90 μm in diameter) of all three LRCs and a fine grind (75 wt% smaller than 100 μm) of the North Dakota lignite only.

Samples of the feed and the product from each drying test were carefully examined to characterize the chemical and physical changes in the LRCs and the phenomena causing them. The effluent streams from the steam and hot water drying tests were analyzed to provide complete mass and energy balances. Rheology studies were conducted on slurries of the raw coals and slurries of the dried coals. However, no additives were used in formulating the slurries, as is sometimes done commercially to increase solids loading; nor was there any attempt to optimize particle size distribution and thereby improve slurryability (i.e., increase concentration and reduce viscosity).

Project results

All the drying methods initially reduced the level of coal moisture; however, when the products were later exposed to water and their equilibrium moisture level examined, the results were mixed. (A high equilibrium moisture level generally indicates poor slurryability.) LRCs dried by conventional hot air methods had reabsorbed moisture almost to the original level in the raw coal (Table 1) and therefore yielded no improvement in slurry solids loading (Table 2). In contrast, as also shown in the tables, LRCs dried by steam or by hot water showed substantial reductions (e.g., 3:1) in equilibrium moisture level and yielded improved slurry loading (as high as 60% solids) suitable for slurry-fed entrained-flow gasifiers.

The effects of removing inherent moisture from LRC are most noticeable in comparing the heating values of concentrated slurries (Table 2). For example, the pourable slurries made from lignites dried by hot water or by steam contained 96–97% of the energy of an equivalent mass of raw (as-received) coal; that is, the lignites were slurried with a quantity of moisture similar to that inherent in the raw coal. By contrast, the energy content of slurries of the Illinois and Pittsburgh bituminous coals was about 75% that of the raw coals. The final slurry heating values for LRCs dried by hot water or by steam compared favorably with those of the bituminous coals, a significant finding in that both the Illinois and Pittsburgh coals have shown excellent performance in pilot plant tests in a Texaco gasifier (AP-2814).

In addition to showing good results in terms of solids loading and energy content, the slurries with hot-water-dried lignites were extremely stable. In fact, some of the lignite slurries still had not settled out after months of storage. In contrast, the other slurries, particularly those with the subbituminous coal, were not stable. Although the slurries with steam-dried LRCs showed high solids loading with even lower viscosity than the slurries with hot-water-dried LRCs, they tended to settle without continued agitation and thus are slightly less attractive for commercial applications.

Another advantage of hot water drying is reduced sodium. Although ash removal occurred in both steam and hot water processes, substantial sodium reduction occurred only during hot water drying. As a nonevaporative process, hot water drying may also offer potential energy savings over steam drying.

Table 1
EQUILIBRIUM MOISTURE LEVEL OF DRIED COALS
(% by weight)

Drying Method	North Dakota Lignite	Texas Lignite	Wyoming Subbituminous
Undried raw coal	33.0	31.6	26.4
Rotolouvre drier	29.0	26.4	22.2
Parry drier	28.7	26.0	21.2
Steam autoclave			
270°C	14.8	11.8	8.3
300°C	11.0	7.2	5.6
330°C	8.3	4.8	3.6
Hot water autoclave (coarse grind)			
270°C	19.1	16.1	15.1
300°C	15.2	13.6	11.3
330°C	12.1	8.5	8.7

Table 2
SLURRY SOLIDS LOADING AND HEATING VALUES

Coal and Slurry Qualities	Undried Raw Coal	Hot Air Drying		Steam Drying (autoclave)	Hot Water Drying (continuous)
		Rotolouvre	Parry		
North Dakota lignite					
Solids loading (%)*	43	43	45	58	59
Heating value (Btu/lb)	4300	4500	4500	6400	6300
Texas lignite					
Solids loading (%)	43	42	42	59	62
Heating value (Btu/lb)	4300	4500	4500	6700	6800
Wyoming subbituminous					
Solids loading (%)	48	44	44	58	63
Heating value (Btu/lb)	5600	5600	5300	7300	7600
Illinois No. 6 bituminous					
Solids loading (%)	60	—	—		—
Heating value (Btu/lb)	7700	—	—	—	—
Pittsburgh No. 8 bituminous					
Solids loading (%)	66	—	—		—
Heating value (Btu/lb)	8200		—	—	—

*Percentage by weight, on the basis of bone-dry solids.

Future efforts

This work confirms that hot water drying has the potential to yield a concentrated, pumpable LRC-water slurry and thus to improve LRC performance in slurry-fed entrained-flow gasifiers. The promising results of this initial phase of study have led to further experiments to examine the fundamental parameters that govern the hot water drying process, including residence time and the actual temperature of solids during the drying period. Developing a viable continuous process for hot water drying requires that consideration also be given to the separation of excess slurry water from the solids after drying and to slurry heating methods.

EPRI's work complements the studies planned for the DOE pilot plant project, which will address scale-up issues for the overall hot water drying process. Further studies must provide a basis for determining the costs and benefits of integrating the drying and slurry preparation steps with a gasification plant.

In summary, steam and hot water drying processes have potential for increasing the range of coals economically suitable for slurry-fed gasification–combined-cycle plants. They could also increase the geographic market for the conventional use of LRCs—hitherto consumed primarily in minemouth plants. Both processes yield a product of improved quality in these respects: lower equilibrium moisture level, higher heating value (energy density), nonpyrophoric nature, lower sodium content (less fouling), and greater slurryability. These properties markedly enhance the value of the LRC products and would help justify their transportation to centers of use. EPRI will sponsor economic studies in the near future to determine how the costs of preparing these improved fuels compare with their increased value. *Project Manager: George H. Quentin*

INTEGRATED TWO-STAGE LIQUEFACTION

A major emphasis of EPRI's Clean Liquid and Solid Fuels Program is the development of two-stage liquefaction (TSL) technology, which is believed to have the potential to substantially reduce the cost of coal-derived alternative fuels. TSL uses two reaction stages to liquefy coal, in contrast to the H-Coal and Exxon Donor Solvent processes, which use only one liquefaction stage. When its advantages are fully exploited, TSL promises to offer high yields of acceptable-quality fuel oils with near-minimum hydrogen consumption.

The potential for product slate flexibility is important to the utility industry, which requires a spectrum of liquid fuels heavier than gasoline. Although initial TSL operations efficiently produced low-sulfur solid fuel (solvent-refined coal, or SRC) and substitute residual fuel oil, researchers concluded that further investigation was necessary for the efficient production of distillable fuels. This report describes the progress of that work, which is being conducted at EPRI's pilot plant test facility in Wilsonville, Alabama. (The overall Wilsonville project is cosponsored by EPRI and DOE and managed by Southern Co. Services, Inc.; Catalytic, Inc., operates the facility. Standard Oil Co. of Indiana joined the project in 1984 as a contributing participant.)

In the initial TSL operations at Wilsonville (*EPRI Journal*, June 1982, p. 41), the two reactors acted independently; the residual product of the first (thermal) stage was upgraded in the second (catalytic) stage. This early nonintegrated system was well suited to producing either a very low sulfur solid fuel similar to SRC or synthetic No. 6 fuel oil.

Reactor system integration was considered to be the least complex, and hence the next logical, step toward achieving product flexibility. In contrast to the two stand-alone reactors of the TSL system, the integrated two-stage liquefaction (ITSL) system uses reactors that work together: the hydrogen-rich solvent from the catalytic reactor (or hydrotreater) is recycled back to the thermal coal conversion reactor. Thus the hydrogenation ability of the catalytic reactor is used to enhance the performance of the noncatalytic coal conversion reactor.

Operation of the ITSL system began in November 1982. Since then, significant performance improvement has been achieved by varying the thermal reactor parameters and other operating conditions. A sustained benchmark run to demonstrate steady performance with regular catalyst addition and withdrawal was completed in February 1984. The run showed that ITSL is a viable process for producing high-quality distillable fuel; defined the response and interaction of primary variables; and demonstrated that the efficiency of hydrogen use can be increased through ITSL system optimization.

Following the benchmark run, which used high-sulfur bituminous coal, a series of operations with a low-sulfur subbituminous coal was conducted. The primary objective of these runs, completed in August 1984, was to demonstrate the operability of all process units in the all-distillate mode, which involves the production of net coal products boiling below ~1000°F (540°C). Other objectives were (1) to assess the performance of a once-through, disposable catalyst (porous iron oxide and dimethyl disulfide) in the thermal coal conversion reactor, and (2) to demonstrate two recycle configurations: the ITSL configuration used in previous bituminous coal operations and a double-integrated two-stage liquefaction (DITSL) variation (Figure 1).

As reported at DOE's Direct Coal Liquefaction Contractors Conference, held in October 1984 in Albuquerque, New Mexico, the subbituminous runs showed that the ITSL system can operate efficiently in the all-distillate mode. The iron-sulfur catalyst successfully promoted coal conversion, achieving a 92% conversion rate. As shown in Table 3, all-distillate product slates were produced with both the ITSL and DITSL configurations.

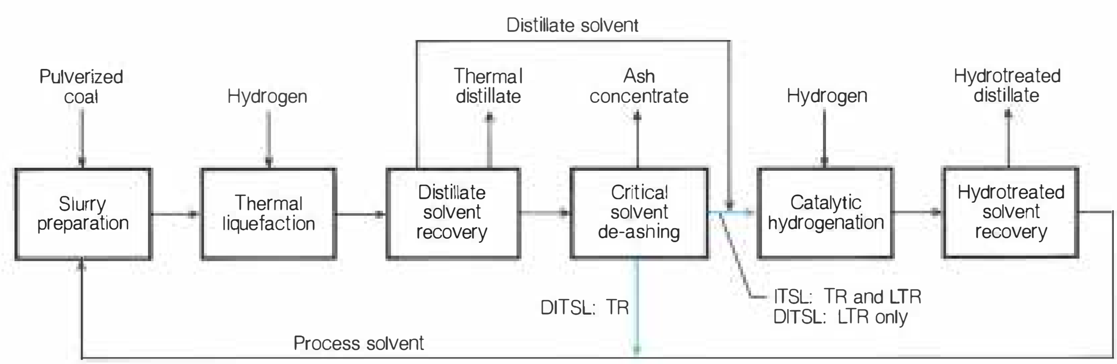


Figure 1 Two process configurations for two-stage liquefaction were tested in the subbituminous coal runs: integrated TSL and double-integrated TSL. The main difference between the two involves the de-ashed coal thermal product (color arrows). In ITSL the whole product is fed to the second reactor for catalytic hydrogenation. In DITSL the product is fractionated into light thermal resid (LTR), which is fed to the catalytic reactor, and thermal resid (TR), which is recycled.

Table 3
TSL PERFORMANCE BY CONFIGURATION AND BY COAL TYPE

	Configuration (subbituminous coal)		Coal Type (ITSL configuration)	
	ITSL	DITSL	Subbituminous	Bituminous
Yield (% moisture- and ash-free coal)				
C_1–C_3 gas (total gas)	9 (19)	9 (18)	9 (20)	7 (12)
Water	13	13	11	10
C_4 and distillate	52	54	54	59
Resid	2	2	2	4
Hydrogen consumption	5.3	5.7	5.4	5.3
Hydrogen efficiency (lb C_4 and distillate per lb H_2 consumed)	9.8	9.5	10.0	11.1
Distillate selectivity (lb C_1–C_3 per lb C_4 and distillate)	0.17	0.17	0.17	0.12
Energy content of feed coal rejected to ash concentrate (%)	22–24	21–24	20–24	20–23

Not only did the operation fulfill the stated objectives, it also demonstrated product yields from subbituminous coal comparable to those previously achieved with bituminous coal. Table 3 also compares two runs using the different coals. Hydrocarbon products (i.e., C_1–C_3 gas and C_4 and distillate) totaled 63% for the subbituminous coal and 66% for the bituminous coal. Coal carbon content (% of moisture- and ash-free coal) was 73.5% for the subbituminous and 76.7% for the bituminous. On the basis of carbon content, the yield of hydrocarbon products from bituminous coal would be expected to be about 3% greater than that from subbituminous coal.

In the ITSL work, the distillable product yield (from moisture- and ash-free coal) has been increased by 25% over the previously demonstrated H-Coal and Exxon Donor Solvent processes. Plans for the future focus on the engineering refinement of the ITSL system. *Subprogram Manager: Norman Stewart*

R&D Status Report
COAL COMBUSTION SYSTEMS DIVISION

Kurt Yeager, Vice President

POWER PLANT WATER CHEMISTRY CONTROL

Water is essential to the electric utility industry. Power plants use it in a variety of ways, ranging from a boiler makeup process fluid to an equipment coolant to a transport medium for combustion waste products. Growing environmental concern about water conservation and surface water contamination has led to requirements for greater recycling of plant process waters and to limitations on potential pollutants in plant aqueous discharge streams. These factors, together with dwindling fresh surface water supplies in many parts of the United States, constrain power plant siting, design, and operation. Utilities must obtain permits to discharge wastewaters and must comply with effluent limitation guidelines established by the EPA or state agencies. Also, they must deal with the operational problems resulting from water recycling—for example, corrosion and/or mineral scaling of process equipment, which can lead to plant efficiency losses, increased maintenance, and reduced plant reliability. Two continuing EPRI water quality control projects address these problems. One is establishing guidelines for improving the design and operation of recirculated-cooling-water systems (RP1261); the other is developing a new process to remove trace elements from aqueous discharge streams (RP910).

Cooling-water chemistry control

There are several approaches utilities can take in dealing with decreasing water supplies and tighter effluent restrictions. One is to maximize the use of water in plant process systems by recycling. This is feasible up to a point—that is, until dissolved solids begin to cause operational problems like scaling and corrosion.

Because cooling-water systems demand the greatest amount of makeup water and are critical to power production, much of EPRI's water chemistry research has concentrated on them. In these systems calcium carbonate, calcium sulfate (gypsum), and silica may present mineral scaling problems, depending on the quality of the source water. These precipitates may form insulating deposits on the surfaces of condensers, piping, and other process equipment, which degrade overall plant performance and force plant maintenance outages. In 1978 EPRI initiated a long-term project (RP1261) to develop, demonstrate, and verify a comprehensive set of design and operating guidelines for effective cooling-water chemistry control (*EPRI Journal,* July/August 1979, p. 38). These guidelines will give architect-engineers an improved basis for making design decisions and plant engineers a reference for achieving reliable system operation.

Preliminary guidelines were issued in March 1982 (EPRI CS-2276). They present a detailed methodology for sizing cooling systems and estimating treatment option costs, as well as general operating rules of thumb. The guidelines also greatly expand on previously published information by including two new computer models for simulating cooling-system operation (CLGTWR) and the associated aqueous chemistry (DRIVER).

As part of a continuing effort to upgrade and improve the preliminary guidelines, a portable cooling-system field test unit (FTU) was constructed and was operated at two sites. The first site was the Comanche station of Public Service Co. of Colorado, where tests took place during 1981 (RP1261-4, -6). They focused on the prevention of calcium carbonate and calcium sulfate scaling for a high-calcium (150–215 ppm as $CaCO_3$) makeup water.

The site 1 test results indicated that the commonly accepted operating rules for calcium scaling control ranged from extremely conservative to adequate. However, the guideline computer models more accurately predicted the potential for FTU condenser scaling and therefore appear to advance the understanding and control of cooling-water chemistry. Three EPRI reports summarize the site 1 test results (CS-3852, CS-4040, and CS-4076).

Site 2 testing (RP1261-8) has recently been completed at Sierra Pacific Power Co.'s North Valmy station, which has high-silica (60–75 ppm as SiO_2) makeup water. Results from these tests will contribute much needed data on the ill-defined chemistry of silica in water. A survey of 22 power plants with high-silica makeup water showed that almost all were operated well below the commonly accepted control limit (150 ppm as SiO_2) for silica scaling. The scarcity of reliable information and a resulting lack of utility confidence account for this conservative approach. They also account for the limited use of softening treatment: at only five of the plants was any attempt made to improve cooling-water chemistry by removing silica in a makeup or sidestream softener. A preliminary review of the site 2 FTU data has already shed light on several important aspects of aqueous silica chemistry.

The traditional operating guideline (i.e., the 150-ppm SiO_2 limit) appears to be very conservative. Table 1 shows that silica precipitation in the FTU did not occur until this guideline had been exceeded by at least 65%. Even at high SiO_2 concentrations in the FTU recirculating water, the formation of silica scale in the condenser was so slow that an increase in pressure drop was not detected for 48 hours. This finding suggests that the strategy of operating cooling systems well below the accepted guideline may not be taking advantage of a certain built-in conservatism. Further, barring extreme system upset, silica scaling in condensers is probably gradual, which would allow adequate time to adjust system chemistry.

Equally as important are the FTU data on softening and silica removal. Although silica can be effectively removed in makeup and sidestream softeners, the actual removal mechanism has not been completely understood. Consequently, it has been difficult to op-

Table 1
SITE 2 FTU RESULTS

Test Sequence	Maximum Silica (ppm)*
No treatment	320
Makeup softening	250
Sidestream softening	265

*Concentration in the recirculating water before precipitation was noted in the FTU.

timize softener operation. One of the most frequently proposed mechanisms involves the adsorption or coprecipitation of silica on magnesium hydroxide [$Mg(OH)_2$]. However, laboratory tests run before the FTU tests indicated that silica may be removed by a solid solution of the general form $Mg(SiO_2)_x(OH)_{2-x}$. These laboratory studies also indicated that silica removal would be more rapid in a sidestream softener than a makeup softener.

A preliminary evaluation of the FTU results supports the laboratory study conclusions. Two types of magnesium compounds were used as additives in the FTU makeup softener: ionic magnesium compounds and precipitated magnesium compounds. Ionic compounds ($MgCl_2$, $MgSO_4$) tend to dissolve in a softener so that ionic magnesium (Mg^{++}) is produced and is available to react with other ionic species. Precipitated magnesium compounds [MgO, $Mg(OH)_2$] tend to form a magnesium hydroxide floc, which provides ample surface area for adsorbing other species, but which does not readily ionize so that magnesium can participate in other reactions.

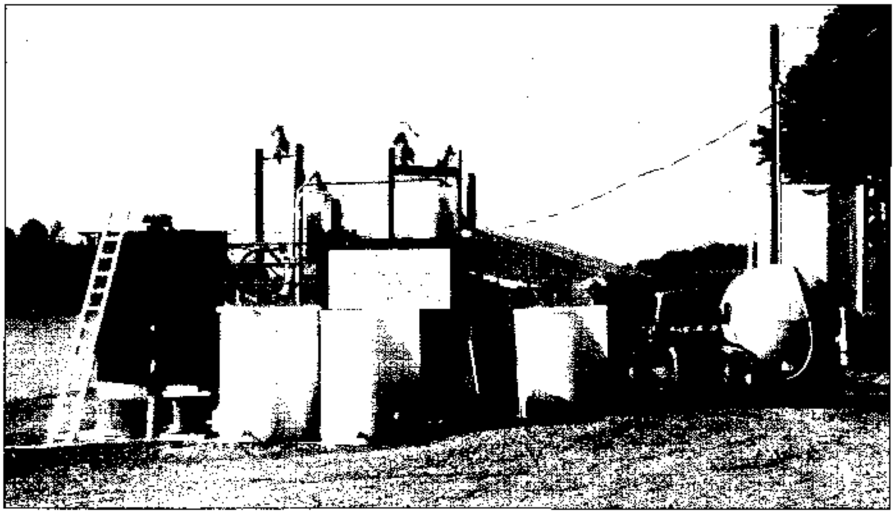
In the FTU makeup softener, the use of an ionic magnesium compound was significantly more effective than that of a precipitated magnesium compound. Almost 10 times more precipitated magnesium was required to achieve comparable silica removal. These results support the proposed solid-solution mechanism, which relies on the reaction of ionic magnesium with silica. Since most softening systems currently use a precipitated magnesium compound additive, these results could offer utilities a way to improve silica removal and/or reduce operating costs for softening systems.

In addition, the FTU results confirmed that silica removal was more rapid in sidestream softening than makeup softening. This difference can probably be attributed to the higher inlet silica concentration and consequently the higher driving force for reaction.

Other FTU softener data indicate that over the range tested (0.2–1.7 wt%), the solids content of the water had little influence on silica removal. However, recycling sludge to the flash mix zone caused a 25–135% increase in silica removal. Neither residence time nor pH variations (10.8–11.2) showed much influence on silica removal.

Although the FTU data evaluation is preliminary, the potential benefits of these test results may be considerable. Utilities may be able to use this new information on aqueous silica chemistry to improve their control of plant condenser scaling and softener operation. The final site 2 test results will be published later this year in a two-volume report. The design and operating guidelines manual (CS-2276) and the mainframe computer models (CLG-TWR and DRIVER) will also be updated to reflect the results of FTU testing at both sites.

Figure 1 This test unit was constructed at Carolina Power & Light Co.'s Roxboro station to evaluate the iron adsorption/coprecipitation process for removing trace elements from power plant aqueous discharge streams. The results of the initial tests, which focused on selenium and arsenic removal, are very promising.



Effluent treatment

To satisfy regulatory requirements, some utilities must consider plant design modifications to reduce or eliminate specific pollutant emissions. One option is to remove the target trace constituent chemically from the aqueous process stream. Under RP910 a novel chemical treatment process for removing trace elements from utility wastewaters was developed. This process entails the physical adsorption of aqueous trace elements onto iron hydroxide precipitate in a reaction-contact system. An earlier status report described the various options for applying the process and discussed the results of extensive laboratory, engineering, and comparative economic studies (*EPRI Journal*, May 1984, p. 44).

The prospects for commercializing this iron adsorption/coprecipitation process appear to be excellent. The low cost and the selectivity of the process for removing a number of trace elements—such as arsenic, selenium, copper, nickel, chromium, zinc, lead, vanadium, and cadmium—are its outstanding attributes. An example illustrates its economic appeal. With the mechanical processing option, a 90% reduction of arsenate (the +6 oxidation state of arsenic) would cost about $380 per million gallons of treated ash pond effluent. This compares favorably with the cost of using conventional lime–soda ash precipitation for the same purpose, which is $560 per million gallons. The technical feasibility and potential benefits of the new process are discussed in CS-4087.

To demonstrate the performance of the iron adsorption/coprecipitation process under actual plant operating conditions and to verify its technical and economic advantages, a test unit was constructed at the four-unit, 2100-MW (e) coal-fired Roxboro station of Carolina Power & Light Co. (Figure 1). This continuous-flow, 35-gal/min (132-L/min) mechanical process test unit was operated at Roxboro for over 2½ months. The performance results were quite promising and seem to confirm the earlier laboratory and feasibility test data that indicated it was possible to reduce pollutant concentrations down to low $\mu g/L$ (i.e., ppb) levels.

The station's ash pond effluent contains selenium (40–60 $\mu g/L$) and arsenic (20–40 $\mu g/L$), both of which are commonly found in coal-fired power plant wastewaters (CS-3744). For this particular test ferric chloride ($FeCl_3$), an iron salt compound, was added to the wastewater to form the ferric oxyhydroxide precipitate. It is on the iron oxide sites of this precipitate that the selenium and arsenic then adsorb.

In this process, trace element removal depends on six major variables: the oxidation state of the trace element, its influent concentration, the iron dose, pH, the reaction or clarifier overflow rate (i.e., the rate of treated-wastewater production), and any chemical interference caused by competing ions in the wastewater. On the basis of information derived from preliminary laboratory jar tests using effluent samples taken from the station, the researchers determined that a reaction pH of 6.0 would yield the maximum removal of both arsenic and selenium species. The iron dose was varied from 7 to 56 mg/L, and the clarifier vessel treated-effluent overflow rate was varied from 400 to 1200 gal/ft^2/d (16,300–48,900 L/m^2/d). Higher iron doses produced lower concentrations of the target species in the treated effluent (Figure 2), and particulate carry-over in the treated effluent rose in direct proportion to the clarifier overflow rate.

The preliminary field test results demonstrate the efficacy of the technology. Arsenic was efficiently removed. Both forms of arsenic, arsenite (the +3 oxidation state) and arsenate (the +6 state), were strongly adsorbed onto the iron precipitate. With iron doses of 14 mg/L and more, total arsenic removal consistently exceeded 90–95%. Residual concentrations were less than 2 μg/L. Up to 80% removal of total selenium was achieved, given initial wastewater concentrations ranging from 40 to 55 μg/L. Considering that about 20% of the initial selenium was in the poorly reactive selenate form (+6 oxidation state), the selenite (+4 state) removal achieved appears to closely corroborate earlier bench-scale results and performance predictions. As anticipated, the high sulfate concentrations, which are characteristic of coal-fired power plant ash ponds, interfered with the adsorption of the selenate ion, retarding its removal.

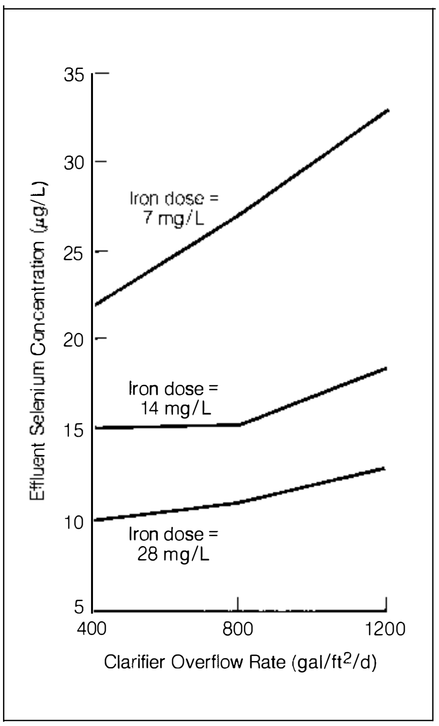


Figure 2 Effect of iron dose and clarifier overflow rate on effluent selenium concentration. In these tests the influent selenium concentration ranged from 43 to 57 μg/L and the reactor pH from 6.0 to 6.6. At higher iron doses, effluent selenium levels were less sensitive to the clarifier overflow rate (i.e., the treated-wastewater production rate).

Table 2
TEST RESULTS FOR IRON ADSORPTION SLUDGE LEACHATE

Substance	Measured Concentration (μg/L)	EPA Limiting Concentration (μg/L)
Arsenic	<1	5,000
Barium	2,500	100,000
Cadmium	20	2,000
Chromium	<20	5,000
Lead	<100	5,000
Mercury	<0.2	200
Selenium	<1	1,000
Silver	<10	5,000

One recurring question during the technology's development concerns whether the treatment sludge generated from this process could be considered hazardous under the Resource Conservation and Recovery Act. If so classified, the sludge would require special handling and disposal, which means increased treatment cost. Therefore, as part of this study, a sample of the process sludge from the test unit was subjected to the EPA's extraction procedure (EP) toxicity test. When the leachate was analyzed, no substance exceeded its limiting concentration of 100 times the federal Safe Drinking Water Standards (Table 2). This result is encouraging and significantly improves the outlook for broad utility application of the technology.

Extensive sludge thickening and dewatering test data are currently being analyzed. A final report presenting the complete field test results and the upgraded process economics is scheduled for publication this summer. EPRI is considering additional field studies to investigate the removal of other trace metals. If such a program is warranted, EPRI will seek another test site, formulate plans, and begin field tests early in 1986.

Other efforts

As concerns over the environment and the efficient use of water resources continue to grow, utilities are evaluating opportunities for managing plant water consumption and discharge in a way that is consistent with their air quality control and solid waste disposal practices. Through projects such as the two discussed here, EPRI is seeking to produce research results and develop technologies that will ensure (1) the proper integration of water management requirements with those for air and solid waste, (2) plant system operating reliability and availability, and (3) compliance with all applicable environmental statutes.

Other EPRI water quality control projects in progress focus on discharge monitoring and analysis (RP1851), various aspects of integrated power plant water management (RP2114), and condenser biofouling control (RP2300). As part of EPRI's continuing commitment to technology transfer, two major symposia are upcoming: one on condenser biofouling control (June 1985) and one on power plant water management (February 1986). All these activities are part of an estimated $11.9 million EPRI will devote to water quality R&D between 1985 and 1989. The products of this research will enable utilities to optimize plant process water chemistry to meet the increasing challenges of water resource availability, plant performance and reliability, and environmental controls. *Project Managers: Winston Chow and Wayne Micheletti*

COAL-CLEANING COSTS

About one-third of all steam coal mined in the United States today must be cleaned to some degree to be acceptable for electric utility firing. Little western coal is cleaned; thus eastern coal, particularly that mined underground, makes up most of this third. Almost 80% of all Illinois coal, for example, requires cleaning. For a utility that burns cleaned coal, the cleaning process significantly increases the reserves of locally available and economically usable coal, and reduces the utility's reliance on more remote reserves and the rail and barge services they entail. The economic ramifications of coal cleaning are therefore important to many utilities that fire eastern coal. An important step in evaluating coal-cleaning economics is estimating the capital and operating costs of alternative cleaning plants. EPRI has undertaken a project to develop a methodology for estimating these costs and to provide supporting data for preparing actual cost estimates (RP2255-1).

Cost model

The design and cost of a coal-cleaning plant depend on many factors, including raw coal characteristics, product quality specifications, and plant location. Further, a designer must assess various process alternatives, each with a different coal recovery efficiency and a different product quality. Each process alternative will have its own capital and operating costs, which form the basis for financial evaluation. Cost estimates are difficult and expensive for a utility to prepare because they require time and specialized knowledge. Yet utilities that do not own coal-cleaning facilities may want to make such estimates to verify the coal-cleaning costs proposed by their coal suppliers. Also, utilities that own coal reserves may want to conduct feasibility evaluations of alternative cleaning processes for a specific coal or to evaluate bids for cleaning plant construction. Inaccurate or insensitive estimates can hamper comparison of the economics of various scenarios; thus utilities need a model for estimating capital and operating costs.

EPRI also needs such a model. At its Coal Cleaning Test Facility (CCTF) in Homer City, Pennsylvania, a wide range of coals undergo large-scale flowsheet characterization in many different cleaning circuits. Test planning and results will be enhanced by the ability to provide capital cost estimates for commercial-scale plants designed on the basis of CCTF results.

Therefore, to provide computational methods and supporting data for estimating the capital and operating costs of modern physical coal-cleaning plants, EPRI began developing a workbook in January 1983. The workbook is designed principally for utility engineers who have some coal-cleaning experience but who have little or no cost-estimating experience. It is intended to serve as a self-sufficient reference but will list appropriate sources for users who need additional data or information. The three-volume workbook will be available in mid 1985.

The aim of the project is to make the model as easy and convenient to use as possible. The workbook provides cost estimates for conventional cleaning plants that process 300–2000 t/h of feed coal; the target accuracy for these estimates is ±20%, which is sufficient for budget authorization. Some advanced processes can also be evaluated, but estimates for them are not as accurate. The workbook covers all plant facilities for all aspects of coal cleaning, from run-of-mine coal handling and storage to refuse disposal and clean-coal handling. Operating cost estimates vary with plant capacity and allow for local conditions. The project also includes a validation task, for which costs of recently built coal-cleaning plants have been used as test cases. The workbook does not provide guidance for using the capital and operating cost estimates in economic analyses; for help in this area, users will need to consult other references, such as EPRI's *Technical Assessment Guide* (P-2410-SR).

Capital cost estimates

The capital cost of a coal-cleaning plant is composed of the construction cost and the owner's cost, which break down as follows.

- Construction cost: total field cost (total direct cost, indirect cost), engineering services, total contingencies
- Owner's cost: land, sales tax, interest during construction, initial chemicals, royalty allowance, inventory capital, preproduction cost

The model concentrates on the calculation of the total direct cost; the other items contributing to total capital cost are calculated from that estimate. The model provides several computational options of varying complexity and detail. The more detailed procedures give users greater opportunity to modify input data and thus improve the model's accuracy and sensitivity.

The basic premise of total direct cost estimation is that almost any cleaning plant can be considered to consist of a small number of standard functional components, such as rotary breakers, fine-coal froth flotation cleaning circuits, clean-coal silos, and electric substations. The model provides technical and cost data on more than 40 of these standard components and covers a wide range of sizes or capacities.

As input data, a model user must have a process flowsheet and a completed mass balance for all streams within the flowsheet. From this information the user determines a list of the components in the flowsheet and their appropriate design capacity or size. From graphs the user can then estimate equipment costs, equipment installation costs, construction material costs for each component, and the cost of subcontracted finishing work (e.g., adding sidings, painting) for each component. Adding these costs together gives the total direct cost.

Limited validation work has been completed, and in Figure 3 model predictions of total construction costs for several plants of different sizes are compared with published and conceptual costs. The model estimates tend to be higher, which may indicate that a more conservative design philosophy is inherent in the model.

Operating cost estimates

The workbook also provides a methodology and supporting data for calculating the annual operating and maintenance (O&M) costs of a coal-cleaning plant. The major components of these costs are as follows.

- Operating and maintenance labor
- Maintenance materials and supplies
- Operating materials and supplies (magnetite, flotation chemicals, thermal dryer fuels, water treatment chemicals, makeup water, and vehicle fuel and lubrication)
- Electric power
- Refuse disposal

In addition to these standard O&M items, it is recommended that users allow for the cost of lost coal. More complex coal-cleaning circuitry can often be justified by its ability to improve the product weight recovery from a given feed quantity while maintaining product quality. Any analysis of cleaning plant options should therefore recognize avoided mining costs.

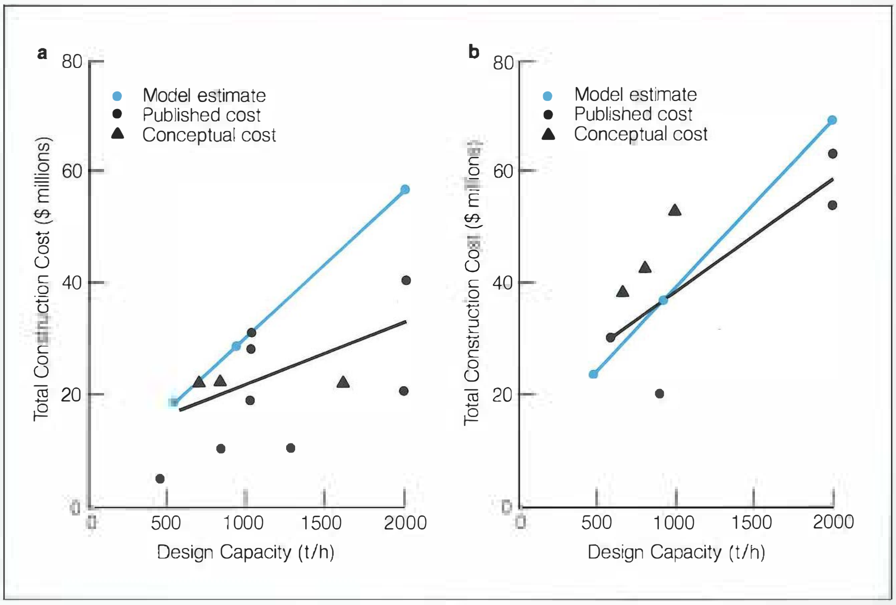


Figure 3 The coal-cleaning cost model was used to estimate total construction costs for two types of cleaning plants at various capacities: (**a**) jig plants and (**b**) heavy-media plants. A comparison of these estimates with published costs and costs from conceptual design studies seems to indicate that the model is based on a more conservative design philosophy. (Costs are given in 1983 dollars.)

Figure 4 Model estimates of operating and maintenance costs were compared with actual plant data for (**a**) jig plants and (**b**) heavy-media plants. Because O&M practices vary, the actual costs are more scattered. (Costs are given in 1983 dollars.)

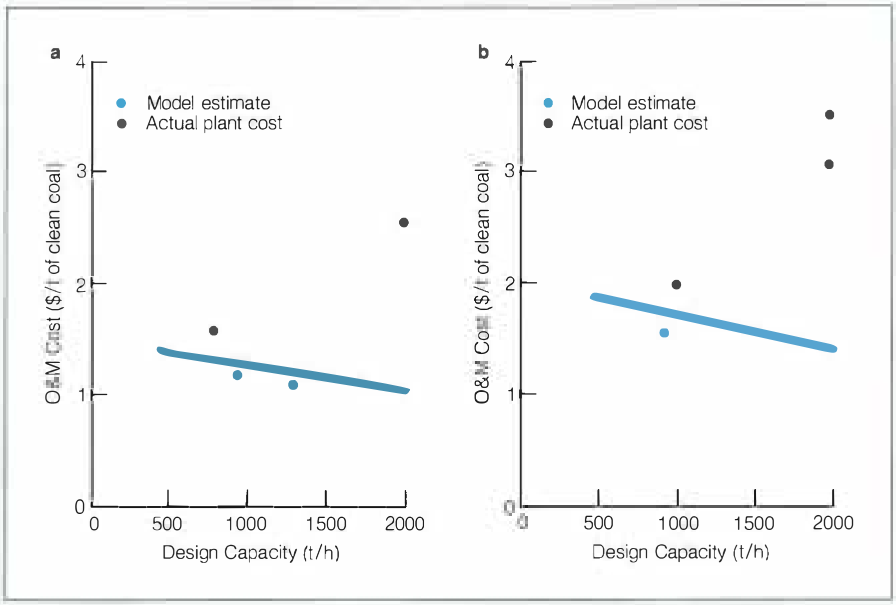


Figure 4 presents validation results for several O&M cost estimates. Because O&M practices vary widely from plant to plant, much more scatter may be expected in actual costs than will be seen in model predictions.

Other cost-related information

In addition to presenting the capital and operating cost model and supporting data, the workbook covers a range of other cost-related issues. It contains information on engineering, procurement, and construction schedules for different plant sizes, as well as likely expenditure rate patterns through the prestartup phases. It discusses such factors as instrumentation and automatic control, plant layout, and the use of installed spare equipment. These factors may significantly add to capital costs and decrease operating costs, but insufficient data are available to quantify the trade-offs. The workbook also covers multiple-product plants, advanced coal-cleaning techniques (including some economic data), and regional cost factors and escalation indexes. *Project Manager: Robert W. Row*

R&D Status Report
ELECTRICAL SYSTEMS DIVISION

John J. Dougherty, Vice President

TRANSMISSION SUBSTATIONS

HVDC converter stations for voltages above 600 kV

High-voltage direct-current (HVDC) transmission systems are an attractive option for moving large blocks of power over long distances. Until recently, 600 kV has been the design limit for HVDC because very little information was available on highly stressed converter station equipment. To determine what barriers might exist to higher-voltage dc, an engineering study of the dc converter station equipment required for a system with pole-to-ground voltages between 800 and 1200 kV was initiated.

The studies, which are expected to provide valuable information for planners and designers, were performed by Themag Engenharia Ltda, Brazil (RP2115-4), and Institut de Recherche de l'Hydro-Québec (IREQ), Canada (RP2115-5), in cooperation with Centro de Pesquisas de Energia Eléctrica, Brazil.

Researchers performed computer studies to determine the characteristics of the major converter components in systems with pole-to-ground voltages of 800, 1000, and 1200 kV. They identified the design requirements for converter transformers, arresters, filters, and bypass breakers for three converter configurations. Next, they prepared simplified equipment specifications (minispecs), which they used to obtain technical feedback from utilities and estimates from manufacturers. Extrapolating from current technology, the project team then analyzed converter station layout and land requirements and determined economic operating voltages on the basis of the rated power to be transmitted, the transmission line configuration, and station equipment power losses. As a final step, analysts calculated the potential costs of dc lines and converter stations and determined economic transmission levels for given line lengths and levels of transmitted power.

The results of the study so far have provided valuable information to guide research on HVDC converter systems. The evaluation of converter transformers, for example, suggests that the use of a single-phase, two-winding transformer is desirable for the very high transformer ratings associated with these high voltages. Arrester analysis suggests that HVDC energy stresses require arresters with a large number of parallel columns. The study also shows that the dc line prefault condition significantly affects arrester stresses, as does dc filter capacitance. Researchers found, however, that very high voltages do not interfere with the performance of filters and bypass breakers.

The economic analysis will help researchers evaluate the industry's ability to develop and deliver equipment for dc converter stations. In general, the study showed that an HVDC system must transmit large blocks of power (about 5000 MW) over relatively long distances (about 400 mi [640 km]) to warrant the use of 800-kV dc, a finding that confirmed expectations. The studies also confirm that HVDC transmission for voltages over 600 kV cannot be built without significant R&D preceding the commercial application of such systems.

Final report EL-3892 has been published for the Themag work. The companion EPRI project under contract with IREQ (RP2115-5) will identify R&D needs for converter station equipment. *Project Manager: Stig Nilsson*

PCDFs in utility equipment

In July 1984 we discussed the start of a multiphase PCB-related project to determine the extent to which polychlorinated dibenzofurans (PCDFs) are contained in utility insulating fluids. The project (RP2028-5-10) has three basic goals. One is to improve the analysis for individual congeners (a congener is defined as one unique compound out of 135 different PCDFs, each having a definite number of chlorine atoms in designated positions on the dibenzofuran rings, such as 2,3,7,8-tetrachlorodibenzofuran); these may vary in physiologic activity (toxicity) in animal tests over a range of at least 1000 to 1. A second goal is to determine the level of PCDFs found in utility equipment that has seen varied use. A third is to develop a screening test to more rapidly determine total PCDF-like activity, to reduce costs, and to reduce time delay in cleanup activities after PCB fires.

The analytic work depended on the use of isotopic carbon spiking compounds, which were not produced on schedule because of difficulty in acquiring the rare raw materials needed for compound preparation. These compounds are now prepared and are being used by the participating laboratories as a partial calibration of the mass spectrometers used for the analysis. Because of this delay, the project was rearranged to first run a mini-round-robin analysis by three laboratories on four in-service samples. The first two samples tested were a mineral oil contaminated with 100 ppm of PCBs from a transformer that had failed in service by arcing, and PCB 1242 removed from a capacitor that had bulged, but not ruptured, in service. Both had PCDF and dioxin levels below the limits of detection. A sample taken from a PCB transformer containing 70% Aroclor 1260 and 30% trichlorobenzene, after 20 years of service, showed detectable quantities of PCDFs and polychlorinated dibenzodioxins (PCDDs). Another sample of the same composition but taken from a PCB transformer of a different manufacturer that had seen 31 years of service showed higher levels of these partial oxidation products.

To supplement the analyses of field samples, a series of laboratory tests was run in which samples of contaminated oil and askarels were subjected to an under-oil electric arc, simulating the action of a faulted transformer. Little, if any, PCDF or PCDD formation was found as a result of the arcing.

Laboratory work is continuing with a statistical analysis of the field samples already tested. Following this, with probable adjustments to some of the analytic techniques, a larger series of approximately 20 samples will be tested by five laboratories. It is hoped that a satisfactory and more useful analytic method will result from this larger round robin. Added arcing tests are being run and will be analyzed to expand our knowledge of the effect of arcing. Simultaneous work will be done with two mass spectrographs in tandem (MS/MS) as a means of screening samples, which bypasses the present costly, time-consuming sample cleanup practice. As part of another contract (RP2028-4), a bioassay method is being calibrated to serve as a low-cost means of screening for total PCDF-like physiologic activity. *Project Manager: Gilbert Addis*

Pyrolysis and combustion of PCBs

As regulations appear to be tightening in the handling and phasing-out of askarel-filled equipment (*askarel* is a generic term for PCBs and mixtures with tri- and tetrachlorobenzene), other transformer insulation fluids also require attention. One of these is mineral oil that has been inadvertently contaminated with PCBs. During the period when PCBs were not considered a problem, many transformers were contaminated either by manufacturers or by utilities when they used common liquid transfer equipment for both PCBs and mineral oil. Several million of these transformers contain 50–500 ppm PCB in the mineral oil and are, by regulation, contaminated. A small fraction of the mineral oil transformers containing PCBs are above 500 ppm and are legally PCB transformers.

A second problem area is that of retrofilled equipment. The mixture of liquids in a transformer after initial retrofill normally is found to have 2–5% of the original PCB remaining; therefore, virtually all retrofilled transformers are still legally PCB transformers. The observation that PCBs under conditions of pyrolysis or combustion can be converted to much more physiologically active polychlorinated dibenzofurans (PCDFs) has led to heightened interest in both types of equipment. A priori, there is no reason to expect that low concentrations of PCBs found in contaminated fluids would produce disproportionately high concentrations of PCDFs on pyrolysis or combustion. However, because the details of the mechanisms by which this conversion occurs are not well established, it is clearly desirable to test this possibility experimentally before launching a major retrofilling program.

EPRI has therefore initiated a project with the New York State Department of Health to determine the rate of PCDF formation under conditions of pyrolysis and combustion (RP2028-4). Initially, tests were made with individual PCB congeners to standardize operating and analytic techniques. These tests have been followed by trials using Aroclor 1254 neat and as 5000- and 50-ppm contaminants in mineral oil and several potential retrofill fluids, such as silicone, perchloroethylene, and RTEmp.

In the pyrolysis of mineral oil solutions at 500, 550, and 600°C, the resultant extracts were analyzed for 2,3,7,8-tetrachlorodibenzofuran (TCDF), total TCDF, total penta-CDF, and total hexa-CDF. Because these results (as well as those of single-congener pyrolysis experiments) suggested maximum PCDF formation at 550°C, the 550°C pyrolyzed neat Aroclor 1254 and 5000-ppm solutions were analyzed for total hepta-CDFs. In addition, these samples will be analyzed in the near future for dibenzodioxins. The results permit some interesting observations, which can be summarized as follows.

- Repeated attempts to detect PCDF formation in 50-ppm solutions of Aroclor 1254 in mineral oil failed, with detection limits ranging from 0.5 ppb for 2,3,7,8-TCDF, 1 ppb for total TCDF, 1.5–3 ppb for total penta-CDFs, and 10 ppb for hexa-CDFs. A future trial at some intermediate PCB level (1000 ppm) will be required to help establish linearity.

- Pyrolysis of neat or 5000-ppm solutions of Aroclor 1254 produces predominantly penta-CDFs, with intermediate concentrations of hexa-CDFs and lower concentrations of TCDFs. Hepta-CDF formation is negligible, as expected from consideration of the congener composition of Aroclor 1254.

Some tasks remain to be completed on the mineral oil portion of the project before preparation of a final report and eventual publication. They are finalization of existing data, including verification of standard concentrations, interinstrument comparisons, and replication of certain key data; determination of concentrations of polychlorinated dibenzodioxins in selected samples; generation of isomer-specific data for 2,3,7,8-substituted penta- and hexafurans; determination of PCDF concentrations in PCB samples before pyrolysis or combustion; and determination of PCDF yields at an intermediate concentration—between 5000 and 50 ppm.

Work involving PCB-contaminated silicone and perchloroethylene is proceeding. Some changes in analytic techniques were required because of the possible formation of traces of unexpected new compounds. Verification of some of these against authentic standards is under way. Additional work is being carried out to calibrate an in vitro bioassay test that could integrate all PCDF-like physiologic activity. *Project Manager: Gilbert Addis*

DISTRIBUTION

Long-life cable development

Performance of distribution cables rated 15–35 kV has been unsatisfactory. High failure rates with cables insulated with high-molecular-weight polyethylene (HMWPE) led the industry to gradually switch to cross-linked polyethylene (XLPE), which is also undergoing a gradual increase in failure rate. Methods for processing such cables differ significantly between the United States and other countries.

In this project, a worldwide survey was performed, encompassing North America, Europe, and Japan; the methodology included questionnaires, a literature survey, telephone interviews, and personal interviews and discussions (RP2438). The information obtained was assimilated and compared, and conclusions were developed.

This work suggests areas that need improvement, particularly for materials handling and extrusion methods. Although the industry is moving toward dry cure (in contrast to steam cure) to keep moisture out of the system, no supplier was able or willing to provide data to support that the curing methods do influence life, and this is information that is urgently required. The position of virtually all the suppliers interviewed is that a proven objective is to meet current industry specifications. However, if the specification requirements do not coincide with real-world aging, the cable reliability will be questionable.

To remain cost competitive, processing characteristics are a major criterion. Improvements in processing-speed characteristics to meet current criteria should receive high priority. Although improvements in processing-speed characteristics to meet current specification requirements are often sought, improvements beyond specification requirements at current processing speeds do not seem to receive consideration. This area is one that requires serious attention. *Project Manager: Bruce Bernstein*

PLANT ELECTRICAL SYSTEMS AND EQUIPMENT

Monitoring turbine generator shaft torsional vibration

Completion of phase 1 of this three-phase project (RP1746) resulted in the successful implementation of the prototype monitor at the Mohave power station, operated by Southern California Edison Co. (Figure 1). Phases 2 and 3—data gathering, event analysis, statistical evaluation—have been under way since May 1983. The data base will include event data from a total of 15 turbine generator shaft systems.

Since the monitoring began, the monitors have captured a total of 35 interaction events, which are in the data base. This is far short of the large number of significant events thought to occur on utility systems. However, users who have the monitors have been able to study system interactions that could result in a cata-

Figure 1 Torsional vibration monitor located at the turbine generator site.

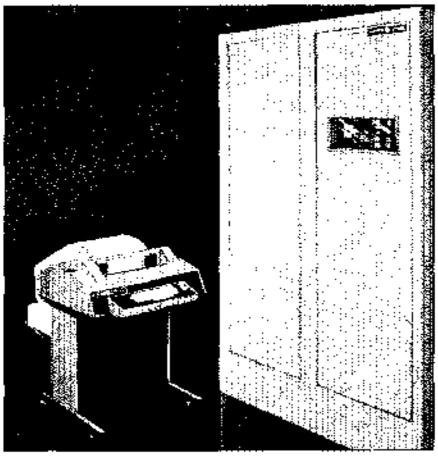
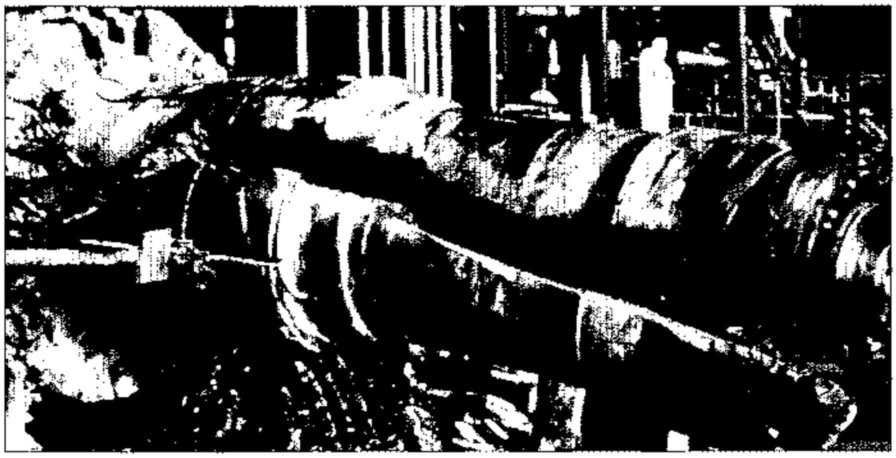


Figure 2 Severe electrical disturbances on utility transmission networks could result in a catastrophic machine failure.



strophic failure similar to that shown in Figure 2, to evaluate operating procedures, and to conduct tests of system protection devices.

To have enough data from which to make valid statistical conclusions on the interactions between turbine generator sets and the electrical system, the project is being extended two years; the new completion date is December 1987. During this time a microprocessor workstation will be completed and installed to support the event data analysis (that work is now being performed on a commercial time-sharing computer). The results of the development of the workstation will be applicable to individual microprocessors that can be used to support the torsional vibration monitors after the EPRI project has been completed.

The monitors have been performing well, and any problems that have arisen have been resolved with a minimum of disruption to the operation of the monitor. *Project Manager: James Edmonds*

UNDERGROUND TRANSMISSION

Economic evaluation of pipe-type cable systems

Because of the large number of restraints, the problem of selecting and comparing different applications of high-pressure, oil-filled (HPOF) cable is most complex. There are variables in cable design, installation, and cooling options with analysis of cable losses; energy costs and load profiles further complicate the task. Among the economic conditions to be considered are capital costs, daily operating costs, and time-of-day generation costs. The objective of this project, therefore, was to develop a versatile computer program for the technical and economic evaluation of HPOF transmission cables that would more readily provide optimal choices for any number of alternative situations (RP7884).

This project resulted in a computer program that analyzes and compares a number of HPOF cable system options by considering various configurations of both steady-state and forced-cooled operation under selected economic constraints. The computer program, now available for use on either VAX or IBM systems, was successfully validated on three 230-kV cable circuits, with oil circulation suitable for future forced cooling. Computer examples were run for 345-kV cable circuits with forced cooling, demonstrating economic assessments of forced cooling for 1-year and 20-year discounted costs. The detailed analysis accompanying the validation and application tests confirmed the program's versatility.

As cable engineers and system planners become familiar with the computer program, they will see its capabilities demonstrated in increasing combinations of thermal and economic evaluations, which will establish a credible data base. The final report, EL-2833, is available from the Research Reports Center. *Project Manager: Stephen Kozak*

R&D Status Report
ENERGY ANALYSIS AND ENVIRONMENT DIVISION

René Malès, Vice President

ANIMAL STUDIES ON ELECTRIC FIELD EFFECTS

A major component of EPRI's research program on the biological effects of electromagnetic fields has been the long-term study of electric field effects on mammals. In the initial work, using Hanford miniature swine (RP799), most parameters proved to be the same in exposed and control animals. However, there was a suggestion of increases in fetal malformations, which occurred in some breedings but not in others. The swine study protocol was then replicated with rats. This study also yielded weak and conflicting results that have not clarified the issue. Thus EPRI is pursuing further studies to determine if there are any consistent effects, outside of statistical "noise." These studies, to begin at two laboratories later this year, will use larger groups of rats and will investigate several field strengths, including one that is about twice as high as those in earlier studies. (An overview of research on the biological effects of electromagnetic fields is presented in the July/August 1984 EPRI Journal, *p. 14.)*

Unequivocal deleterious effects to pregnant animals from exposures to 60-Hz electric fields have not been demonstrated. Some studies have suggested an effect, but such factors as the location of animal cages in the room, microcurrents or microshocks during drinking, and random variation cannot be ruled out as causative factors. Other studies involving more extreme conditions have failed to produce an effect.

At Battelle, Northwest Laboratories, one of the groups prominent in research into possible biological effects of electric fields, a number of short-term studies sponsored by DOE produced the following results. A 6-day exposure to a 60-Hz, 65-kV/m electric field before and during mating did not affect the reproductive performance of either sex. Continued exposure of the females through 20 days of gestation (dg) did not affect the size or morphology of the fetuses. In two subsequent experiments, prenatal and neonatal rats were exposed from conception through 8 days after birth and from 17 dg through 25 days after birth. No statistically significant differences that would suggest impairment of growth or survival of these offspring were found. In the second of the three experiments, 14-day-old field-exposed pups showed some precocious behavior in comparison with a control group of sham-exposed animals; in both the second and third experiments, the 14-day-old pups also showed slower development for some behaviors. The differences between the exposed and control groups were not found when the animals were retested at 21 days of age.

Concern that current flow patterns, and hence possible effects, may be different in larger animals led to work with Hanford miniature swine, including investigations of reproduction and development (RP799-1). This work began in 1976. The results of the swine study, to be published by EPRI later this year, were inconclusive; no clear effect of exposure to the electric field was demonstrated. As a result, EPRI sponsored a study patterned after the swine work but using rats (RP799-1). Figure 1 shows the design of this study, which involved

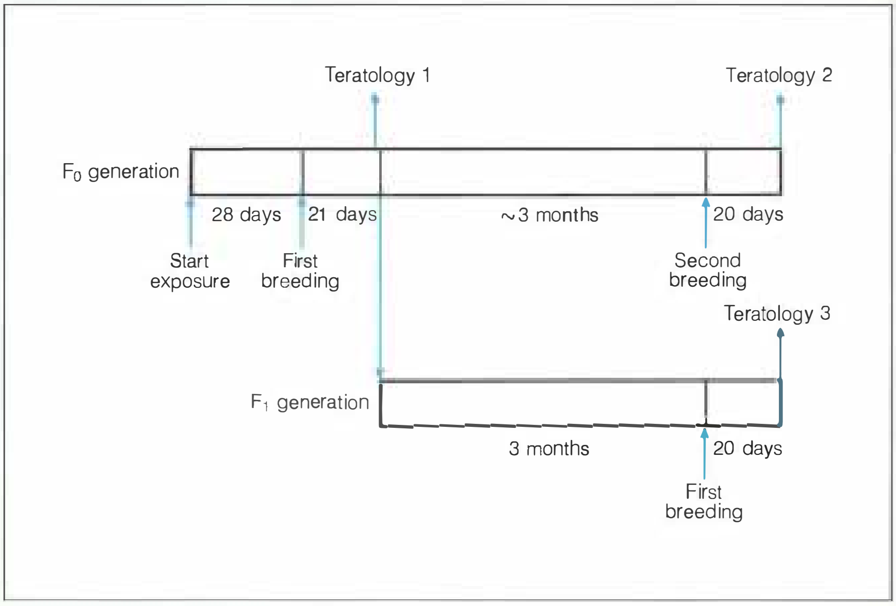


Figure 1 Design of rat study on the reproductive and developmental effects of electric fields. Female rats three months of age (F_0 generation) were exposed to an electric field of 65 kV/m for four weeks and then bred with unexposed males. Some females were sacrificed at 20 days of gestation for teratology 1 examinations. Others were allowed to bear their young and were continued in the electric field; these were bred again and sacrificed for teratology 2. Some female offspring from the first breeding (F_1 generation) were exposed to the field, bred, and sacrificed for teratology 3.

Table 1
RAT RESULTS ON FETAL MALFORMATION

	Litters With Malformations/Total Litters		Probability Value
	Exposed Group	Control Group	
First experiment			
Teratology 1 (F_0)	1/22 (4.5%)	0/21 (0%)	0.50
Teratology 2 (F_0)	6/20 (30%)	2/20 (10%)	0.12
Teratology 3 (F_1)	6/37 (16%)	1/42 (2.4%)	0.04*
Replicate experiment			
Teratology 2 (F_0)	1/27 (3.7%)	2/24 (8.3%)	0.46
Teratology 3 (F_1)	1/37 (2.7%)	3/37 (8.1%)	0.31

*Statistically significant difference.

two experiments, the second a replicate of the first. Table 1 summarizes the results, which were also inconclusive, as discussed below.

Starting at three months of age, the initial generation of female rats (the F_0 generation) was exposed to an effective electric field of 65 kV/m for 20 hours a day for four weeks. The animals were then bred with unexposed males. For the first teratology, some of the pregnant females were sacrificed at 20 dg and the fetuses examined. As shown in Table 1, of the 22 litters from the field-exposed rats that were sacrificed for teratologic examination, one had a malformed fetus, compared with none for the litters of the 21 control rats that were sacrificed. These results are statistically indistinguishable, as indicated by the probability value of 0.50. (By convention, a value of 0.05 or less is usually taken to indicate a statistically significant difference.)

Other rats from the exposed and control groups were allowed to bear their young to produce an F_1 generation. The exposed F_0 females were kept in the electric field and, like the control rats, were rebred at a little over seven months of age with a different group of unexposed males. The females were then sacrificed at 20 dg for teratology 2. While there were more litters with malformed fetuses in the exposed group (30%) than in the control group (10%), these results are not significant, as indicated by the probability value of 0.12 (Table 1).

Finally, for teratology 3, pups in the F_1 generation were bred at three months of age with the same unexposed males used for the second breeding of the mothers. Two females from each litter were selected at random for use in this breeding. In this case the fetal examinations showed significantly more malformations, by litter, in the exposed group than in the sham-exposed control group.

The experiment was replicated, using the same design except that the first teratology was omitted. In the replicate experiment there were no significant differences between exposed and control animals in either teratology 2 or teratology 3

The results of the rat study might perhaps best be characterized as inconclusive or suggestive. The increase in malformations that occurred in teratology 3 of the first experiment did not show up in the second experiment. Because the results suggest the possibility of a small but real difference between exposed and unexposed animals, both for the rats and for the swine, it has been speculated that the field strengths used were at the lower limit of where effects might begin to occur. To ensure clarification of this question, EPRI is planning to sponsor replicate rat experiments at two laboratories that will use both higher and lower field strengths than used in the earlier work.

In developing the experimental protocol, care has been taken to ensure that the study focuses on the teratologic effects question rather than merely mimicking again the swine study, which was originally designed as a screening exercise. The need to have all experimental conditions in the two laboratories as similar as possible led EPRI to sponsor the design, development, and construction of special integrated cage and exposure systems (RP799-18). These systems have been completed and are being readied for delivery.

Fields of approximately 150 kV/m, or about twice as high as those used in the earlier rat study, are contemplated for the upcoming work, as well as fields of 65 kV/m (the same as in past experiments) and background-level fields. To ensure that the rats will be able to function normally under the highest fields, EPRI had Battelle perform a pilot maximum-tolerated-dose (MTD) study. Different groups of rats were exposed to fields of over 140 kV/m and about 110 kV/m. There was also a sham-exposed control group. The rats were exposed for 20 hours a day, beginning at three months of age, and were bred with unexposed males after one month of exposure. The pregnant animals carried the pups to term. The parameters of interest involved the ability of the rats to breed, complete gestation, and rear their young.

Because the rats tolerated the maximum field strength used in this study, a true MTD was not established. However, above the maximum field strength used here, effects such as corona and ozone production occur. Thus a 150-kV/m unperturbed field is the upper limit for investigating possible electrical effects. The results of the MTD study clear the way for the upcoming investigation.

It should be noted that public exposures around transmission lines are significantly lower in terms of strength (probably never more than about 10 kV/m) and duration (minutes or, at most, hours). However, the high dosages planned for the rat study conform to the traditional way of testing for possible dangers (e.g., testing of food additives) to ensure human safety beyond a reasonable doubt.

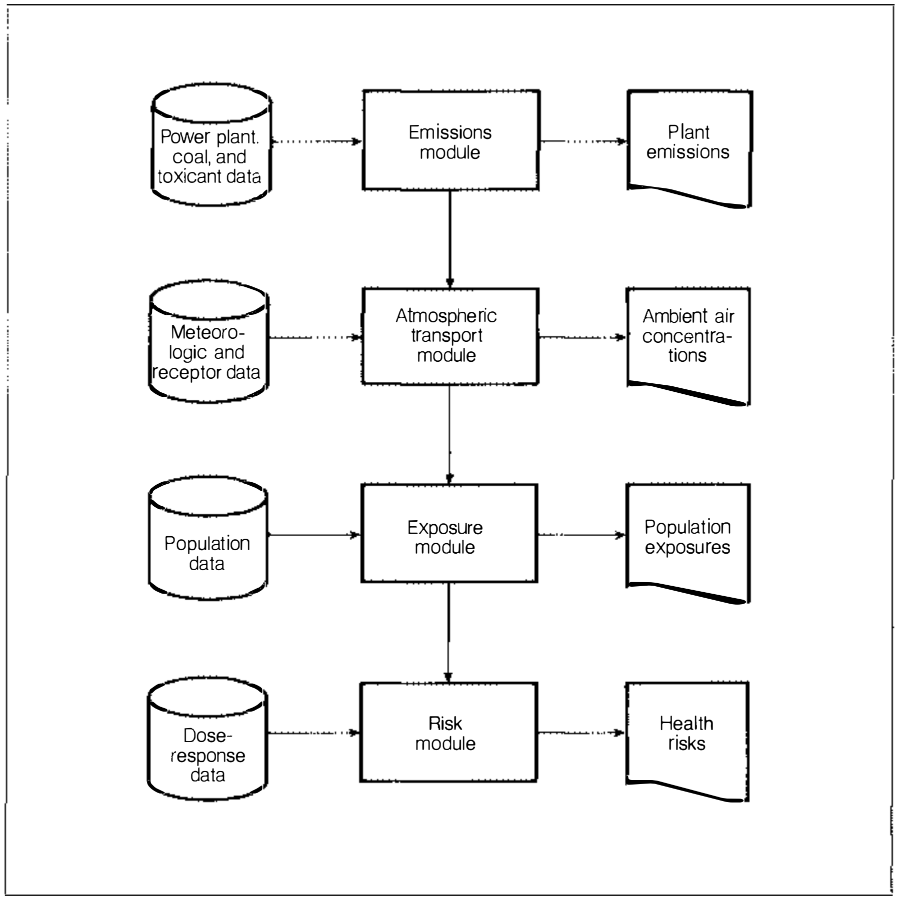
In summary, unequivocal teratologic effects attributable to electric field exposures have not been demonstrated in either the swine or the rats. Because the results can be considered inconclusive, however, EPRI is planning major investigations at two laboratories to provide further data. It must be borne in mind that no amount of experimental effort will ever demonstrate that there are no effects from electric fields; there is always the possibility that one more experiment will uncover something. Results from the upcoming study will be weighed with those from previous work in evaluating whether electric fields can induce malformations in experimental animals. *Project Manager: Robert M. Patterson*

RISK ASSESSMENT: AIR EMISSIONS FROM COAL-FIRED POWER PLANTS

EPRI has developed a model called AERAM (air emission risk assessment model) to evaluate the possible effects on humans from exposure to air pollutants emitted by coal-fired power plants. The pollutants include trace metals and other chemicals that fall within the scope of Section 112 (national emission standards for hazardous air pollutants, or NESHAP) of the Clean Air Act. The model calculates emissions, airborne transport, exposure, *and health risks associated with those pollutants. It is described in EPRI EA-4021 (forthcoming).*

Licensing and operating decisions call for estimates of the effects of coal-fired power plants on human health. One specific area of concern involves the possible effects of trace metals and other chemicals regulated under the NESHAP provisions. Unfortunately, there is great uncertainty about the way plant emissions travel and are chemically transformed to contribute to ambient concentrations and human exposures. There is even greater uncertainty about the effects on humans of low-level exposures to such substances. Despite uncertainties, however, estimates of these parameters have been accepted for regulatory purposes. To facilitate the calculation of possible health effects, EPRI is sponsoring research to consolidate the accepted approaches and estimates used in this field (RP1946). This work has resulted in the development of a model, AERAM, that simplifies the operations needed to make risk assessments.

Figure 2 This model, called AERAM, has been developed for estimating the potential health risks associated with atmospheric emissions from coal-fired power plants. Its modular structure simplifies data preparation and facilitates the evaluation of various risk reduction strategies.



Model capabilities

AERAM consists of a computer code and a set of methods for estimating any excess human cancer risks that may result from exposure to organic and inorganic air pollutants emitted by coal-fired power plants. The methods should help utility decision makers evaluate power plant emissions strategies in terms of their potential for reducing any cancer risk. The model allows utilities to address public and regulatory concerns about potential risks. It is constructed to consider coal characteristics, power plant operation, control technology, the dispersion of pollutants, the exposure of human populations, and the resulting risks. Fuel characteristics and the efficiency of pollution control devices can be varied in order to evaluate the impact on potential human health risks.

AERAM is written in the FORTRAN language and can be implemented on a mainframe computer or on an IBM-compatible personal computer. The code consists of four modules: emissions, atmospheric transport, population exposure, and health risk (Figure 2). It uses data files that are created before running according to formats described in the user's manual. Sample input data are supplied with the code and are documented to facilitate data input. Once the data files are created, the code can be executed in either a stepwise or a continuous manner.

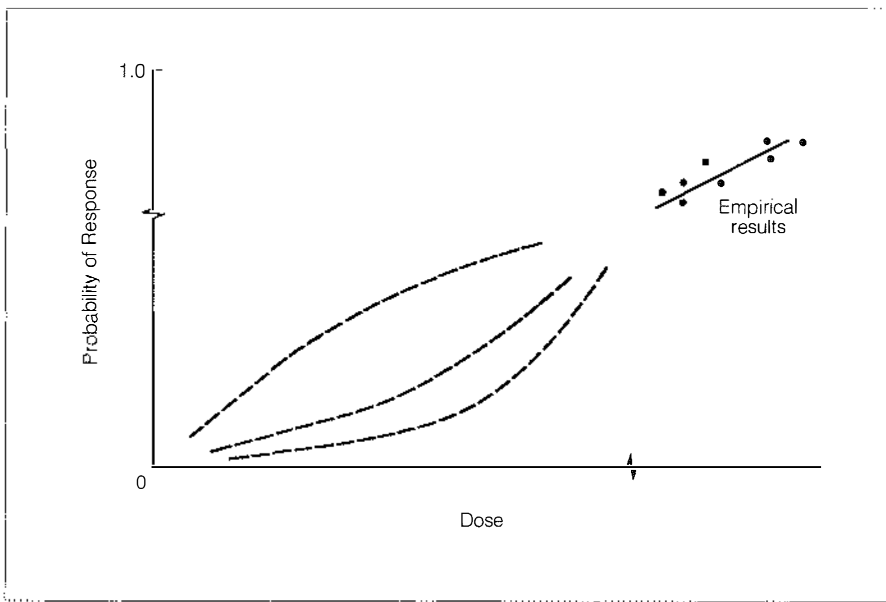
Given data on coal characteristics and power plant operating conditions, the emissions module calculates stack emissions (in units of mass per unit time) for a specific pollutant, as well as the distribution of particle sizes. The efficiency of control devices is also taken into consideration. To determine the concentration of the pollutant in the fly ash, the user can choose either the mass fraction method or the enrichment ratio method. In the mass fraction method, the pollutant's concentration is determined from the particle size distribution and the collection efficiency of the control device. In the enrichment ratio method, the amount of pollutant leaving the stack is calculated on the basis of the pollutant's enrichment of the fly ash relative to another element, normally aluminum.

Next the atmospheric transport module transforms the calculated stack emissions into ambient air concentrations by using the Environmental Protection Agency's ISCLT (industrial source complex long-term) dispersion model. The main input for this module is meteorologic data in the form of a STAR (stability array) summary. The output is an ambient pollutant concentration for each receptor site.

The exposure module links the transport and risk modules by estimating population exposure on the basis of the concentration calculated for each receptor site, the amount of air inhaled by a person, and the number of people at each site. The user inputs the population and inhalation data. The population data can be disaggregated to focus on the exposure of specific age groups or other cohorts. Additional refinements, for example, indoor/outdoor activities, can easily be included.

The risk module calculates cancer risk in excess of background on the basis of animal studies, epidemiologic data, or other assumptions relating exposures to effects. Three dose-response functions are available for extrapolating empirical results to the low-dose region; the user selects a function and then statistically fits it to the available data. If the data are from animal studies, carcinogenic potency

Figure 3 AERAM contains three dose-response functions for extrapolating empirical results on health effects at high doses to the low-dose, low-probability region (gray). The dashed lines indicate possible extrapolations from fitting these functions to available data.



must be converted from the animal species to the human. The three dose-response functions are based on different theories of carcinogenesis. It is hoped that by including these functions, the cancer risk estimates will bound the true value. Given the uncertainty and lack of knowledge about cancer processes, however, the actual risk at such low levels of exposure may be virtually zero.

The risk module requires three data points for each dose level—the number of subjects exposed, the number of subjects with tumors, and the dose administered. The three dose-response functions available in AERAM for extrapolating these data are the one-hit, log-probit, and multistage functions. They were selected because of their current use in the scientific and regulatory communities. This approach allows a user to take full advantage of available, accepted information, as well as to account for regulatory choices regarding the dose-response function. Figure 3 shows representative differences in health effects estimates that result from using alternative dose-response functions.

The output of the risk module consists of excess lifetime cancer risk for various populations or subpopulations in the area of study. Two risk estimates are made for each of the three dose-response functions: individual (per capita) risk and the total risk for the appropriate population.

First use

Health risk analyses using AERAM were recently performed for Northeast Utilities' Mt. Tom coal-fired power plant in Holyoke, Massachusetts. Arsenic and benzo-a-pyrene (BaP) emissions were analyzed to evaluate excess lung cancer risk in the surrounding population. For arsenic the total lifetime risk for the entire population at risk was estimated to range from 10^{-3} (i.e., one chance in 1000 of one cancer developing over the lifetime of the entire population exposed) to 10^{-9} (one chance in one billion), depending on the assumptions made. The corresponding risk for BaP ranged from 10^{-4} to less than 10^{-11}. (To put these figures into perspective, it should be noted that in 1981 approximately 420,000 people in the United States died of cancer from all sources of exposure, including genetic factors.) The individual (per capita) lifetime risk estimates ranged from 10^{-8} to 10^{-14} for arsenic and from 10^{-9} to less than 10^{-16} for BaP. Sensitivity analyses found the risk results to be insensitive to the number of particle size classes used.

In conclusion, AERAM is being developed as a method of analyzing the cancer risk related to atmospheric emissions from coal-fired power plants. Because the code is modular, it allows for convenient data preparation. Data prepared for a specific power plant can be used to study several alternatives. For example, meteorologic and population data could be the same in all simulations for a particular power plant; changing the coal type would require changing only the emissions module input. The AERAM code fills the need for an integrated method of quantitatively assessing cancer risks from atmospheric emissions on the basis of currently available information. Companion software for analyzing health risks associated with solid and liquid wastes in groundwater is also under development. *Project Manager: Paolo F. Ricci*

R&D Status Report
ENERGY MANAGEMENT AND UTILIZATION DIVISION

Fritz Kalhammer, Vice President

COMPRESSOR CONTROLS FOR COMMERCIAL AND INDUSTRIAL APPLICATIONS

Large commercial and industrial compressors are major consumers of electric energy and major contributors to utility peak demand. Recent EPRI research under RP2224 has identified the cost-effectiveness of applying microprocessor-based controls to new and existing compressor systems to improve energy end-use efficiency and reduce peak demand.

Large compressor systems (over 30 hp) consume more than 16% of all the electric energy used in the U.S. commercial sector and more than 13% of that used in the industrial manufacturing sector. The total electric energy consumed by these large compressor systems exceeds 144 billion (10^9) kWh/yr. Most of this energy is used in four applications: commercial and industrial space conditioning (47.8 billion kWh/yr); industrial and food-processing refrigeration (21.1 billion kWh/yr); industrial air compression (32.6 billion kWh/yr); and petroleum and chemical processes (42.9 billion kWh/yr).

Brewery study

EPRI's initial investigation of compressor controls indicated the technical feasibility and cost-effectiveness of using advanced compressor controls in a large domestic brewery (RP1088). The brewery controls provided timely adjustment (modulation) of compressor suction, interstage, and discharge pressures to satisfy instantaneous refrigeration loads while minimizing instantaneous energy use and peak demand. This approach is in sharp contrast to the common practice of operating compressors to satisfy the most stringent pressure or temperature requirements, even though these are seldom, if ever, encountered.

The brewery study indicated that large reductions in energy use and peak demand could be achieved with minimal hardware implementation costs and with no negative impacts on the production process or product quality. Over $75,000 a year was saved at low energy and peak demand costs of 3¢/kWh and $3.25/kW/mo; hardware costs were under $5000. Although improvements in compressor efficiency were found to reduce (by 20–30%) the amount of superheat energy available for recovery by a compressor heat recovery system, the study concluded that heat recovery was still cost-effective.

For the future the study cited the need for a major analytic effort to examine actual compressor system operating requirements (time-variant pressures and flow rates) and to identify optimal compressor control strategies. It also concluded that because manual controls are too cumbersome, automated controls are required for long-term implementation. This work is documented in EPRI EM-2208 and summarized in an earlier *Journal* status report (January/February 1982, p. 48).

Other applications

On the basis of the successful brewery study, a follow-on project was initiated to assess the potential use of compressor control techniques in other applications (RP2224). This study found that compressor capacity modulation control techniques like those developed for the brewery were cost-effective in reducing energy use and peak demand in a wide range of commercial and industrial compressor systems. Table 1 summarizes the project results.

For the commercial and industrial space-conditioning applications examined, energy savings ranged from 16% to over 22% and peak demand reductions from 10% to 20%. Similar energy savings and peak demand reductions were identified for the other applications, which included industrial and food-processing refrigeration systems, industrial air compressors, and a petroleum industry compressor system. Control implementation costs were quite small for most of the applications, and projected payback periods were typically six months to two years. In cases where existing control systems could be modified to achieve the required enhancements, implementation costs were minimal.

In cases involving multiple compressor systems, it was found that significant energy savings and peak demand reductions could often be achieved by selecting the most efficient compressor or combination of compressors and/or by simple shutdowns of excess capacity (as necessary to match instantaneous load requirements). At one site, a large boiler soot-blowing compressed-air system, potential savings of over $212,000 a year (at 1.46¢/kWh) were achievable by simply turning off an unneeded 3000-hp compressor. At another site, a cold-storage warehouse, savings of $28,000 a year could be achieved by optimizing the sequencing logic used in operating an 850-hp

Table 1
TYPICAL BENEFITS OF COMPRESSOR CONTROLS IN COMMERCIAL AND INDUSTRIAL APPLICATIONS

	Space Conditioning	Process Cooling and Refrigeration	Air Compression
Number of sites analyzed	4	5	5
Range of compressor system sizes (hp)	164–2180	300–3100	500–12,750
Energy savings (%)	16–22	10–34	3–15
Peak demand reductions (%)	10–20	9–28	2–10
Cost savings ($)	5,000–70,000	3,500–235,000	8,000–448,000
Payback periods (mo)	3–30	18–24	1.2–30

compressor system composed of several smaller (50- to 200-hp) compressors. Similar potential cost savings were identified for multiple compressor systems used in a large commercial building complex and a large industrial space-conditioning application.

It was found that the magnitude of potential energy savings and peak demand reductions from the compressor capacity modulation control techniques examined in the project depended on three main factors: the size (or capacity) of the compressor system, the magnitude and duration of load fluctuations, and the need for year-round operation.

Smaller compressor systems, those under 30 hp, are often too small to yield the energy savings and peak demand reductions necessary to justify the implementation of more sophisticated controls. For larger compressor systems, the magnitude of load variations (as indicated by changing discharge pressure or on-line capacity requirements) is the primary indicator of the potential for capacity modulation controls. Where large compressor load variations are encountered—the case in nearly all applications—the effectiveness of using suction pressure modulation techniques to achieve energy savings and peak demand reductions is significantly greater than where minimal load variations are encountered. Where the available capacity of the compressor system is significantly lower than that needed to satisfy operating requirements (i.e., the compressor system is at full load for all, or nearly all, its hours in operation), the effectiveness of using capacity modulation control techniques is greatly reduced.

For refrigeration and cooling systems, the need for year-round operation is also a primary indicator of the potential for compressor capacity modulation controls. If a system is operated year-round or even for extended periods in the cooler spring and fall months (when discharge pressures can be greatly reduced), compressor discharge pressure modulation can provide significant reductions in energy use and peak demand. This control option uses improved cooling tower or evaporative condenser fans and/or pump control techniques to produce marked increases in compressor operating efficiency during the cooler months of the year.

Current and future efforts

To verify the energy savings and peak demand reductions available through compressor capacity modulation control techniques, field tests are now being conducted for three representative applications: a 1900-hp single-stage ammonia refrigeration system in a large bakery; a 3100-hp two-stage ammonia refrigeration system in a large meat-processing facility; and an 11,060-hp multistage air compressor with a capacity of 30,000 standard ft^3/min (14 m^3/s) that is used for boiler soot blowing at a large coal-fired utility plant. When these field tests are completed, the project will focus on developing analytic tools (calculation procedures, computer-based programs, and supporting data) for use by compressor system owners/operators and utility customer representatives in evaluating the cost-effectiveness of compressor control techniques in commercial and industrial applications. Plans call for these analytic tools to be released to selected utilities for field validation in late 1985. General release is scheduled for the summer of 1986. *Project Manager: I. Leslie Harry*

ZINC CHLORIDE BATTERY ENERGY STORAGE SYSTEMS

*The several potential advantages that batteries offer over power generation alternatives continue to spur the development of zinc chloride and other advanced batteries (*EPRI Journal, *April 1980, p. 6; September 1980, p. 47; October 1981, p. 6; January/February 1983, p. 49). Research on zinc chloride batteries for utility application has been part of EPRI's Energy Storage Program for over 10 years; since 1978 DOE has funded battery research as well. Reliable operation of 50-kWh zinc chloride modules at 62–68% electrochemical energy efficiency has been achieved, and a 500-kWh prototype battery has been tested at the Battery Energy Storage Test (BEST) Facility. Gulf + Western Industries, Inc., through its subsidiary that developed the zinc chloride technology, Energy Development Associates (EDA), expects to make the first prototype demonstration unit available this year. The system, designated by the trade name Flexpower, will initially be offered in a 2-MW, 6-MWh size (Figure 1).*

Battery energy storage systems are an attractive technology for meeting future peaking needs by using baseload fuels in off-peak hours to store excess capacity. Batteries can also offer utilities (1) rapid response characteristics for meeting system regulation, load-following, and spinning reserve requirements, and (2) small, modular packaging for optimally meeting increased demand requirements and providing broad siting capability. The economic benefits of these special features can range from $100 to $400 per kW.

Of the four advanced batteries under development for electric utility application (sodium-sulfur, zinc bromide, zinc chloride, and redox), only the zinc chloride system has the potential to be commercially available in the near future—at least four years ahead of the others. This report reviews progress on the technology since 1981 and outlines plans for the immediate future.

In 1981 a new cylindrical electrochemical stack design was adopted for the previously developed 50-kWh load-leveling zinc chloride

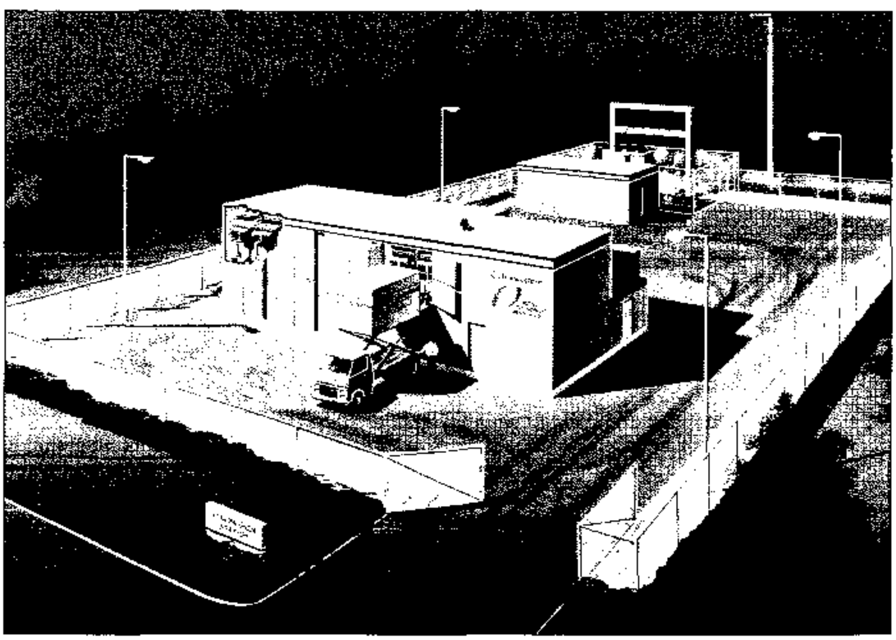


Figure 1 This conceptual design shows a 2-MW, 6-MWh Flexpower installation, the result of over 10 years of research on zinc chloride battery energy storage technology. Prototype hardware for testing of the modular system is expected to be ready later this year.

module. For over 170 full-capacity cycles, an experimental module of the new design operated at an electrochemical energy efficiency (dc to dc) of 60–64%. Further evidence of the operability and performance stability of this design was provided by the assembly and testing of two companion 50-kWh units. The success of this prototype program, which is reported in EPRI EM-3136, prompted a commitment by EPRI, DOE, and Gulf + Western to a follow-on program for the delivery of a 100-kW, 500-kWh system to the BEST Facility in Hillsborough, New Jersey. This facility, built in order to test prototype battery systems for electric utility energy storage applications, is operated by Public Service Electric & Gas Co. (PSE&G) on behalf of DOE and EPRI.

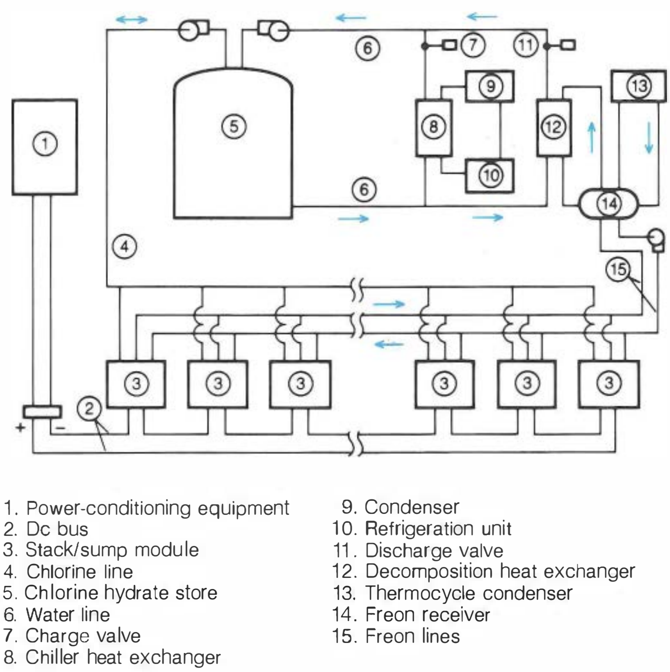
Ten 50-kWh modules were built, tested individually, and connected in series to form the battery subsystem. The complete 500-kWh system, comprising the battery, power-conditioning, control, and refrigeration subsystems, was first assembled in a Detroit Edison Co. utility substation in downtown Detroit. During a seven-week period in May–July 1983, this system underwent qualification testing and satisfactorily performed 11 full-capacity cycles.

BEST Facility testing

Following disassembly, the 500-kWh system was shipped to the BEST Facility in August 1983. The system was reassembled and was completely operational within four weeks. Twenty startup cycles were performed to check out the system. During these cycles the delivered energy averaged 472 kWh, and the electrochemical energy efficiency averaged 63.3%; maximum values were 505 kWh and 64.4%. The startup phase was successfully completed in December 1983.

PSE&G assumed overall test responsibility for the 500-kWh system in February 1984 to provide an independent evaluation of zinc chloride battery technology in utility service. In the first phase of the PSE&G test program, 30 baseline cycles were accumulated during February–March 1984 (EM-3836). The 500-kWh system demonstrated an operating availability of 91% and delivered an average of 94% of its nominal storage capacity. The second phase of testing demonstrated the system's ability to stand fully charged for 6–8 hours before discharge without significant efficiency and capacity losses. The concluding phases of the PSE&G test program involved demonstrating the battery system's capabilities to perform peak-shaving, load-leveling, spinning reserve, load regulation, and area regulation duties, as well as to operate in the modes anticipated for mass transit and industrial mill peaking duty.

Figure 2 The power-conditioning, battery, and refrigeration subsystems of the Flexpower zinc chloride system. The 2-MW, 6-MWh load-leveling system features 16 stack/sump modules and a single chlorine hydrate store.



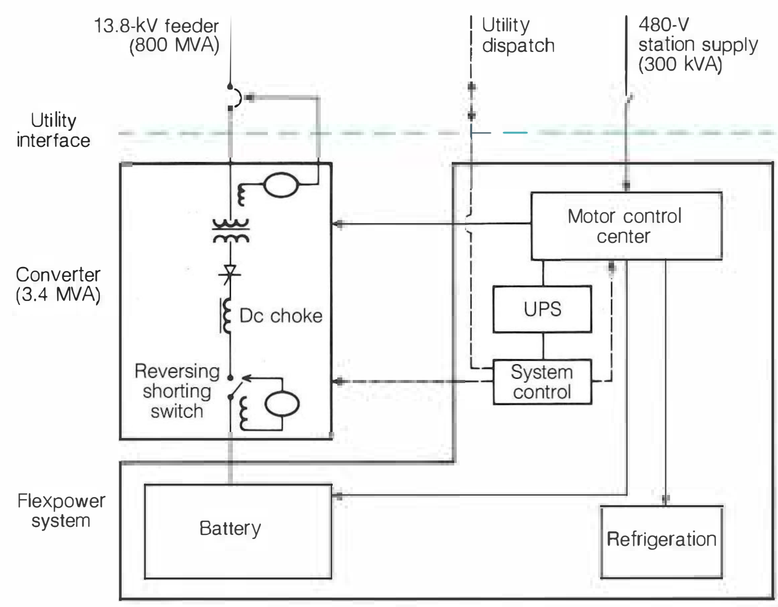


Figure 3 Electrical and control configuration for the Flexpower system. Power links are indicated by solid lines, communications and control links by dashed lines.

Through these tests a substantial data base on component and subsystem performance and reliability has been accumulated. Total operation at the BEST Facility encompassed 102 cycles and 163 runs with a total throughput of 50 MWh of dc energy. The electrochemical energy efficiency of the system slipped from 62.7% at the start of the test program to 56.8% at the end. However, performance remained in the 59–60% range for the modules (four of the ten) using an improved plastic frame material that will be the choice for future load-leveling systems. The system was operated 109 out of the 205 working days of the test program. System availability was difficult to assess in the later test phases because of the time dedicated to software development and checkout and to system maintenance associated with the developmental tests.

Flexpower system

In 1984 EDA designed new prototype hardware by improving the technology built for the BEST Facility. The proposed load-leveling system, called Flexpower, is sized at 2 MW and is to deliver at least 6 MWh over 3 to 7 hours of operation. System sizing was heavily influenced by the desire to use similar hardware to meet both utility markets and markets on the customer side of the meter.

The Flexpower system comprises six major subsystems: battery, refrigeration, power conditioning, safety, environmental, and control. The battery subsystem consists of sixteen 125-kW stack/sump modules, arranged in two tiers, and a single chlorine hydrate store. Each stack/sump module is serviced by a separate electrolyte pump. The 16 modules are connected in series to form a battery that charges and discharges at average voltages of 1170 V and 970 V, respectively. The corresponding currents are approximately 1600 A and 2300 A. Thus the battery is designed to charge at an average power of about 1.4 MW and to discharge at a little over 2 MW. For early prototype units, the electrochemical energy efficiency (dc to dc) is targeted at 65–70% and the overall efficiency (ac to ac) at 50–60%. When the systems are in full production, the overall efficiency will be improved to over 65%.

Figure 2 shows the interconnections between three of the six subsystems to create an operating battery. Each of the 16 stack/sump modules is connected to the dc bus network. Each is also piped to a single chlorine line that leads to the gas pump of the central chlorine store. A supply line and a return line for each sump cooling coil are provided from the liquid Freon distribution piping. A single water line runs between the central store and the heat transfer subsystem. The electrical and control/data signals routed through the system are shown in Figure 3.

In addition to its larger capacity, the Flexpower system differs from the zinc chloride battery tested at the BEST Facility in the following ways.

- The Flexpower system has a single chlorine store instead of a separate store for each stack/sump module.
- The electrolyte sumps and their associated pumps have been scaled up by a factor of eight, which enables the use of commercially available pumps.
- The control equipment has been separated from the stack/sump modules to protect it from corrosion.

The inherent characteristics of the Flexpower system—its fast response time, small modular units, and short procurement lead times—will provide electric utilities with a new means of responding to customer demand and load growth where generation or transmission siting is limited. The primary function of Flexpower installations will be energy management, that is, the storage of off-peak energy for recovery during peak demand periods. However, the fast response time will provide additional benefits in the areas of system regulation and spinning reserve.

The system will have minimal environmental impact. The combination of environmental acceptability and 12-month lead times for delivery will enable utilities to respond to localized load growth quickly at the substation and will enable major industrial or institutional users on the customer side of the meter to significantly reduce demand charges.

Commercialization

Modular battery technology addresses the most urgent concerns of the U.S. electric utility industry: the reduction of financial risk by avoiding large-scale, capital-intensive power plants; the maximization of baseload fuels; and the reduction of environmental impacts to the extent possible. Battery installation will offer utilities a favorable way to deal with all these concerns. Recent EPRI projections for the 1990–2000 time frame indicate that by the year 2000 there will be a cumulative market of 4000 to 8000 MW for batteries costing $500–$750/kW. It is also becoming evident that for specific utilities a battery energy storage market exists today.

The testing of the 500-kWh zinc chloride system at the BEST Facility by PSE&G personnel was an important first step in securing utility understanding of this technology. To gain general acceptance, however, a prototype demonstration program is required that will provide the industry with essential performance, endurance, and cost verification. Given such verification, the industry can plan on Flexpower technology as a viable alternative in the late 1980s, when, according to present projections, new generation will be needed to meet peaking requirements.

EDA has developed a commercialization strategy that involves the building and testing of several 2-MW Flexpower systems over the next three years. The first of these systems is scheduled for evaluation at the BEST Facility in 1986. To maximize the impact of this demonstration program, EDA plans to address all potential market segments: the major investor-owned utility systems, municipal and cooperative systems, and customer-side-of-the-meter applications, such as industrial plants with energy-intensive processing, federal government facilities, and major city transit systems. *Project Manager: W. C. Spindler*

R&D Status Report
NUCLEAR POWER DIVISION

John J. Taylor, Vice President

BOLT DEGRADATION

Since 1977, 12 PWR operators in the United States have reported 20 incidents of bolt failure or degradation in primary coolant pressure boundary applications. A recent review of the Institute of Nuclear Power Operations' Significant Operating Experience Report showed that a total of 105 incidents of bolt failure or degradation have been recorded in the INPO data bases from 1971 to 1983, of which 51 occurred in reactor coolant pressure boundary applications. The cause of failure has been either corrosion wastage (CW) or stress-corrosion cracking (SCC). It is worth noting that most of the reported and documented incidents were discovered during normal refueling, scheduled in-service inspections, or maintenance repair outages. The industry's concern is that defects of critical size could go undetected during normal inspection and the bolt fail during operation. Such failure could result in serious malfunctions or even failure of critical components, which could, in turn, result in a loss-of-coolant accident.

In its work with the Atomic Industrial Forum task force to define the scope of nondestructive evaluation (NDE), EPRI funded several research projects to evaluate the state-of-the-art technology for bolt inspection and to provide better procedures for ensuring adequate inspection during planned outages.

Conventional techniques

Conventional ultrasonic techniques for bolt inspection are based primarily on bolt length and on whether the bolt has a heater hole. An angle beam technique has been reasonably effective for bolts with heater holes. For those without holes, 0° longitudinal beam inspection has been the only alternative.

In the 0° longitudinal technique, inspectors use an ultrasonic transducer to detect reflections of a sound beam. The beam travels down the longitudinal axis of the bolt and is reflected by a crack and by the bolt end (Figure 1). The threads also reflect the beam and create a source of "noise," which may hinder attempts to find cracks. Longer bolts become more difficult to inspect because crack signals become smaller and less well defined. At a 2.25-MHz inspection frequency, the maximum length that can be adequately inspected for cracks is approximately 30 in (76 cm). A general guideline for 0° longitudinal inspection is that when the product of the metal path (in inches) and the frequency (in MHz) approaches a factor of 60 and/or the critical flaw-to-wavelength ratio approaches a factor of 1.5, the technique becomes less effective.

Many bolts used in pressure boundary applications are longer than 30 in (76 cm), and their inspection requires another technique. Fortunately, a large number of these bolts have a heater hole extending down to within a few inches of the end, and the hole is large enough for insertion of an ultrasonic shear-wave search unit. Inspectors can use the shear-wave (normally 45–60°) technique to inspect the thread with a short metal path.

New NDE techniques

To solve the problems associated with inspecting long bolts that have no heater holes,

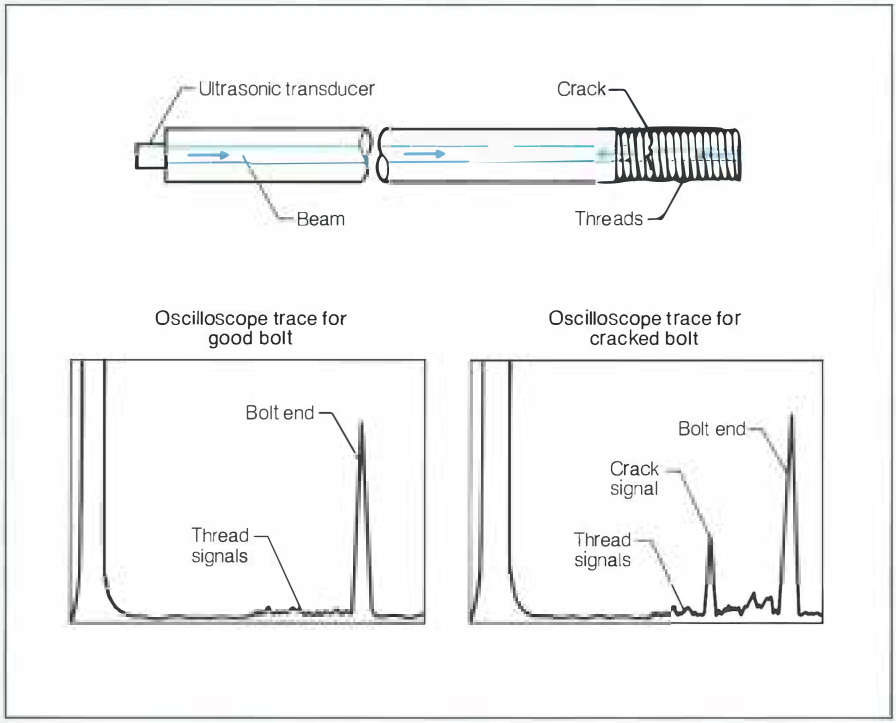


Figure 1 The 0° longitudinal technique. An ultrasonic transducer sends a sound beam down the longitudinal axis of the bolt. In oscilloscope traces for a good bolt and a cracked bolt, spikes at the far left and far right represent the initial energy burst and its reflection from the bolt end. A crack shows up as an additional spike in the low-noise signals reflected from the bolt threads.

EPRI contracted with Sigma Research, Inc. (RP2179-1), Southwest Research Institute (RP-2179-2), and Randomdec Computers (RP-2179-4) to develop and evaluate new techniques that could be applied in the field and that would be sensitive to SCC and CW. Sigma developed the acoustic resonance and reverberation techniques for CW detection; Randomdec Computers extended the acoustic resonance technique for SCC detection; and Southwest Research Institute developed the cylindrically guided wave technique (CGWT) for both CW and SCC detection.

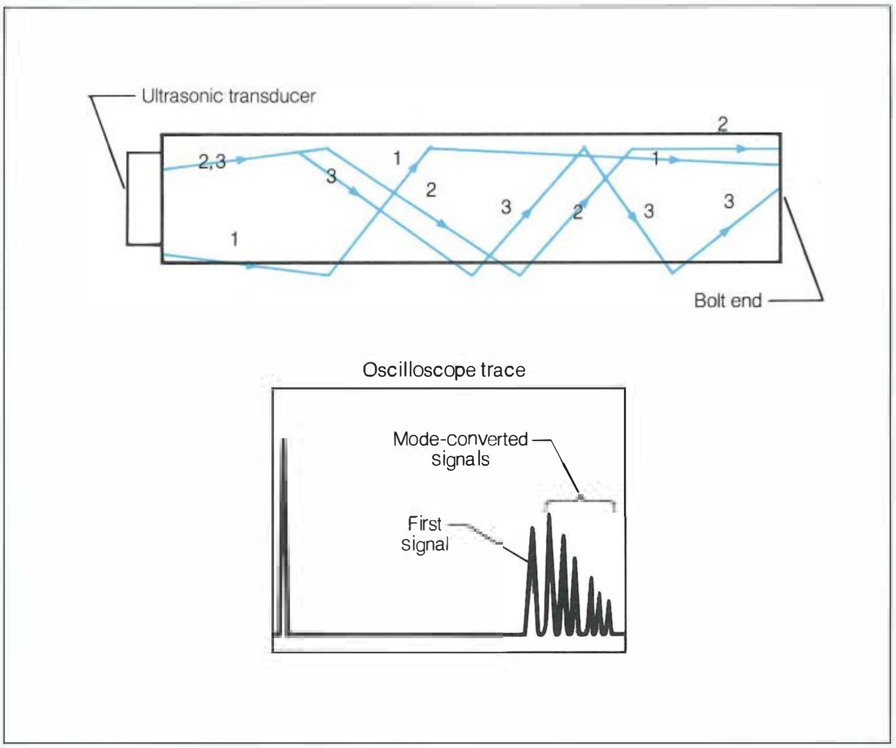
The acoustic resonance technique uses a bolt's natural vibrations. Researchers perceived that any defect in the bolt would alter or modify the natural vibration. In developing the technique Sigma placed two search units on one end of a bolt: one unit as a transmitter of broad-band sound excitation, the other as a receiver for output analysis. The responses from suspect bolts were compared with the response from an unflawed bolt. Sigma demonstrated this approach by using bolt specimens that had been reduced 25% and 50% in diameter to simulate the hourglass shape of CW.

Randomdec Computers evaluated another acoustic resonance technique for SCC detection. This technique mechanically induces longitudinal vibrations in a bolt and measures lateral resonance modes with piezoelectric accelerometers. This technique is based on a theory that assumes bolts have a low damping coefficient and the effect of flaws will be to create a coupling between the longitudinal and lateral vibrations. The mechanical excitation is achieved with a shaker bonded to one end of a bolt; the lateral vibrations at the other end are measured in two perpendicular directions by accelerometers. Randomdec measured the accelerometer outputs and plotted the response versus frequency to obtain a calibration curve based on the response from the unflawed test bolt.

The contractor also used a more elaborate approach, called Randomdec analysis, to analyze the random responses recorded on analog tape during the experiment. This method consists of obtaining a signature, which is the average of all time segments in a random period having the same initial value. These signatures are repetitious if a structure remains unchanged, but they are sensitive to small changes, such as fatigue cracks.

The reverberation technique uses a single search unit centered on the bolt end that is excited with a conventional spike pulser. Inspectors examine the reflected echo sequence to quantify the frequency of the pulse-echo envelope and detect characteristic time spacing changes. This approach is based on the concept that a bolt's physical characteristics will affect an ultrasonic wave propagating back and forth along the length of the bolt. Comparing a bolt's response with that of an unflawed bolt can determine the condition of the bolt under inspection.

Figure 2 The cylindrically guided wave technique. Divergent energy from the transducer undergoes mode conversions at the cylinder boundaries, producing many signal paths (e.g., 1, 2, 3) to the bolt end and still other paths back again. Spikes on the oscilloscope trace show the first, direct return and the return of mode-converted signals that traveled longer paths.



The CGWT is based on the theory that the geometry of a long cylinder, in effect, guides an ultrasonic wave traveling in the cylinder (Figure 2). Instead of exhibiting normal beam spread characteristics, the beam interacts with the outer surfaces of the cylinder to form a succession of mode conversions. This technique has detected saw-cut notches as small as 0.08 in (0.2 cm) deep and 0.8 in (2.0 cm) long at the far end of a bolt. It has also produced good results in detecting simulated CW in bolts reduced 25% and 50% in diameter.

The need for reliably determining the physical conditions of bolts has become an increasingly important task in operating nuclear plants. Some early cases of bolt degradation or failure occurred in studs that were very long, that had no heater holes, and on which conventional techniques were inadequate. The new acoustic resonance and reverberation techniques require unconventional NDE equipment. The resonance technique is sensitive to the presence and location of bolt defects but not to their size. The reverberation technique appears more applicable to CW than to crack detection. The CGWT uses conventional ultrasonic equipment and can be easily applied to bolts. This technique can detect small cracklike defects in long metal paths. It is also sensitive to bolts with CW. Future efforts will evaluate the CGWT on field samples. *Project Manager: Soung-Nan Liu*

ON-SITE SPENT-FUEL STORAGE

The Nuclear Waste Policy Act (NWPA), signed in January 1983, defined more clearly both government and utility responsibilities for the back end of the nuclear fuel cycle. The law made DOE responsible for building waste repositories by 1998 and for the transportation, packaging, and disposal of spent fuel in the repositories. The NWPA made utilities responsible for storing spent fuel until the government could remove the fuel. Utilities are obligated to pay the government's full cost for transportation and disposal of spent nuclear fuel by means of a one-time fee of 1 mill/kWh, which goes to the Nuclear Waste Fund. In addition, utilities must pay for their own on-site storage *until the government transports and disposes of the fuel. Because the federal program may be delayed, many uncertainties affect utility planning for on-site spent-fuel storage. This report discusses EPRI's research, development, and demonstration program for advanced alternative storage technologies to help utilities devise adequate on-site storage. Projects under this program will provide a sound technical base to support NRC licensing activities, as well as build an experience base to enable individual utilities to choose a technology best suited to their particular situation.*

Two changes in spent-fuel storage R&D strategy have occurred over the last two years. The first is the gradual shift away from laboratory-scale projects toward larger-scale demonstrations. These larger projects are a cost-effective way of rapidly demonstrating the technical acceptability of an entire storage system. This approach also provides the experimental data that are needed to confirm analytic models and to support NRC licensing of advanced higher-capacity and lower-cost storage technologies.

The second change in strategy is somewhat related to the first. Because demonstrations require large financial resources, EPRI has established cooperative programs with sponsoring utilities and/or DOE. Such arrangements have proved very successful in that they have allowed EPRI to address a full range of R&D and licensing issues on a tight schedule without exceeding the existing EPRI budget. To date, EPRI has established three such cooperative projects with host utilities; DOE is participating in two of them.

Three recently completed projects illustrate the laboratory-scale activities. In the area of pool storage, work under RP2062-11 has documented recent pool storage experience and identified fuel assemblies now in storage that can serve as test assemblies for such parameters as longest storage time, highest burnup, highest internal pressure, and highest hoop stress. The project results are reported in NP-3765.

Also completed are complementary projects by Battelle, Pacific Northwest Laboratories and by Ridihalgh, Eggers, and Associates, Inc. (REA), which provide thermal modeling and experimental data for consolidated fuel in dry storage. The Battelle work compared the thermal performance of an unconsolidated and a consolidated fuel bundle by predictive modeling of peak fuel clad temperatures (RP2406-2). The project staff also studied the sensitivity of peak cladding temperatures to changes in cover gas (air, helium, vacuum) and variations in rod-to-rod spacing. The work is reported in NP-3764.

REA experimented with an electrically heated scale model to measure temperatures of a consolidated assembly built to simulate a canister containing rods from two BWR assemblies (RP2406-3). The experimental apparatus allowed REA to adjust the test parameters to match the modeling sensitivity studies by Battelle. These parameters included the ability to change the heat generation rate, pin-to-pin gap spacing, and cover gas inside the canister. The experiment results correlated well with the Battelle predictive modeling results. The test results were also encouraging in that they indicated improved heat transfer rates for the consolidated case, especially when the rods were in a helium environment. Publication of the REA project results is scheduled for this summer.

Rod consolidation demonstration

Rod consolidation is the process of disassembling fuel bundles and then close-packing the fuel rods in a canister for maximum density. This technology can increase storage density by a factor of 1.7 to 2.0, depending on the approach used to package and store the scrap hardware. In many cases, this increase can give reactors on-site storage capability for nearly the life of a plant.

However, rod consolidation has some constraints and uncertainties. Handling and disposition of the residual bundle scrap hardware and increased structural loads in storage pools are among the constraints. Uncertainties include the total system costs of consolidation, licensing risks associated with consolidation, consolidation safeguards, and consolidation interface requirements with future DOE fuel disposal activities.

The Northeast Utilities rod consolidation demonstration project, which concludes next year, should clarify many of the uncertainties (RP2240-2). This project, in which Baltimore Gas & Electric Co. and Combustion Engineering, Inc., are also participating, is one of the three major EPRI-supported demonstrations. The objective is to design and demonstrate a state-of-the-art rod consolidation system. The project team will also perform the structural, seismic, critical, and thermal-hydraulic analyses necessary for preparing an NRC license application. Northeast Utilities will then apply for a license to consolidate and store fuel in the Millstone-2 pool. Project sponsors are also considering the generic applicability of the equipment to fuel other than the Combustion Engineering fuel used at Millstone-2.

Key future milestones for this demonstration will be license application and cold demonstration in 1985. A hot demonstration is scheduled for 1986, depending on constraints imposed by the Millstone-2 operating schedule.

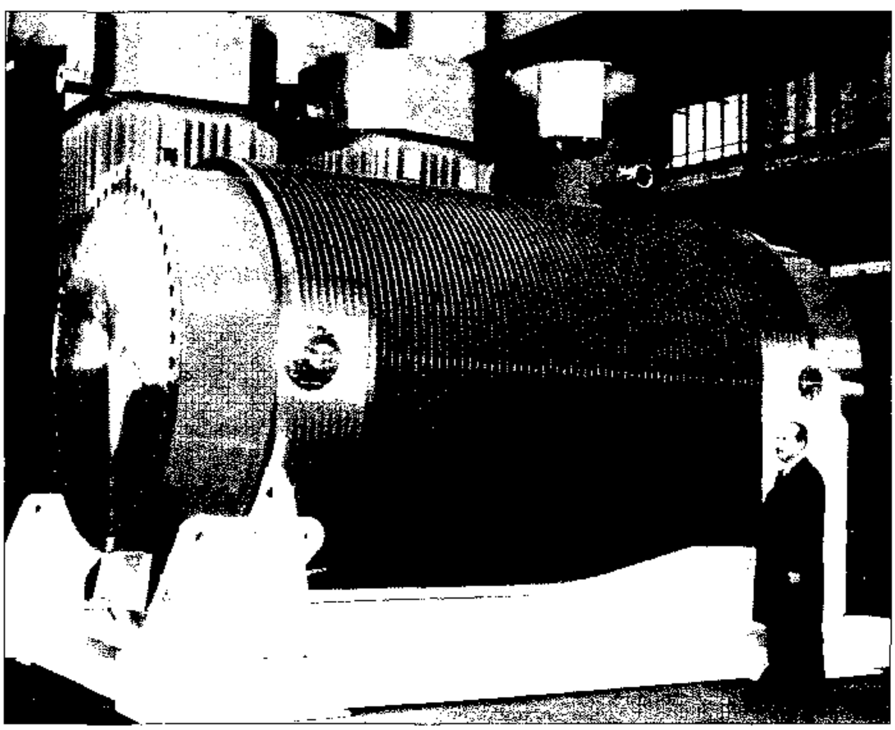
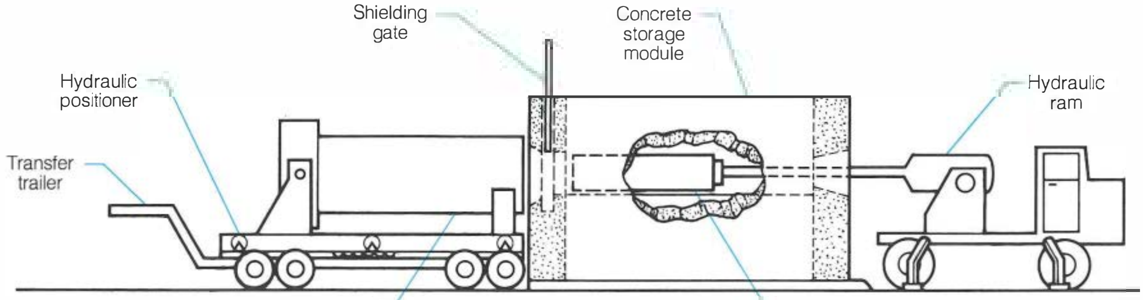


Figure 3 This CASTOR V/21 cask will be the first cask loaded with fuel at the Idaho National Engineering Laboratories test site. The cask weighs about 100 tons and holds 21 PWR fuel bundles.

Figure 4 The NUHOMS spent-fuel storage system consists of a fuel transfer cask, a sealed metal canister that holds the fuel, a concrete storage module, and auxiliary equipment to load and unload the module.



Dry storage demonstrations

Under terms of the NWPA, DOE has entered into cooperative dry storage demonstration projects with both Virginia Power and Carolina Power & Light Co. (CP&L). EPRI has become a partner in both of these demonstrations and is committed to providing financial and R&D support.

The major objective of the Virginia Power program (RP2406-4) is to demonstrate metal cask storage technology. Activities have been divided into two parts. The first is a test series to be conducted at the test area north (TAN) federal test site located at the Idaho National Engineering Laboratories (INEL). The tests include the following objectives and activities.

- Test and demonstrate dry storage, using a range of cask designs and materials
- Test and demonstrate storage of both intact and consolidated fuel
- Test storage over a range of internal cask environments, including air, helium, and vacuum

The second part is a licensed storage demonstration to be conducted at Virginia Power's Surry reactor site. The utility has applied to NRC for a license to store up to 84 casks, each holding about 10 tons of intact fuel.

This cooperative program, which was initiated early in 1984, has already achieved the following key objectives.

- One CASTOR V/21 nodular cast iron cask has been ordered from GNS for use at TAN. It was delivered to Idaho in December 1984 (Figure 3).
- One Westinghouse Electric Corp. forged carbon steel cask has been ordered for use at the Idaho site, with delivery set for early 1986.
- A second CASTOR V/21 has been ordered for use at the Surry site.
- Both GNS and Westinghouse have submitted licensing topical reports, and Virginia Power has applied for the Surry license.
- Fuel characterization has been completed at the Surry plant on fuel to be used in the program.

Fuel shipment to Idaho is planned for the summer of 1985, followed by early placement of fuel in the CASTOR V/21 cask. NRC approvals of the GNS topical reports and the Surry site license application are also expected by mid 1985.

CP&L, EPRI, DOE, and Nutech Engineers are working together on the CP&L project (RP2566-1). The major objective is to demonstrate a licensed horizontal storage module. This system, developed by Nutech and called NUHOMS, consists of a sealed inner metal canister, which holds seven PWR bundles. The canister is stored horizontally in a low-cost concrete shielding module. The canisters will be transported from the reactor to the storage modules in the IF-300 transport cask currently owned by CP&L. Figure 4 illustrates the NUHOMS concept.

The advantages of the horizontal storage module concept are (1) it is expected to cost less than other dry storage concepts; (2) it can be easily integrated into future shipping systems; (3) it is completely modular in design, and major components can be assembled onsite; and (4) the sealed canister design can facilitate final disposition.

CP&L plans to license and demonstrate three storage modules at its H. B. Robinson plant. The project is on schedule. The NUHOMS topical report was submitted to NRC in November 1984, and the CP&L site-specific license application was submitted in February 1985. Fuel is expected to be loaded late in 1986.

EPRI is responsible for documenting and distributing the RD&D results for the three major demonstration projects discussed in this status report. Publication of the first reports is scheduled for mid 1985. Additional progress and design reports will be issued as they become available until the last project terminates in 1988. *Program Manager: R. F. Williams; Project Manager: R. W. Lambert*

New Technical Reports

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

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

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

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ADVANCED POWER SYSTEMS

Feasibility of Gasifying Exxon Donor Solvent Residues in the TVA Ammonia-From-Coal Facility
AP-3897 Final Report (RP1807-1); $8.50
Contractor: Tennessee Valley Authority
EPRI Project Manager: W. Weber

Evaluation of the British Gas Corp./ Lurgi Slagging Gasifier in Gasification–Combined-Cycle Power Generation
AP-3980 Final Report (RP2029-5, -6); $17.50
Contractors: Ralph M. Parsons Co.; British Gas Corp.
EPRI Project Manager: B. Louks

COAL COMBUSTION SYSTEMS

Coal-Water-Slurry Technology Development: Conversion Guidelines
CS-3374 Final Report (RP1895-4), Vol. 2; $17.50
Contractor: Combustion Engineering Inc.
EPRI Project Manager: R. Manfred

Biofouling Detection Monitoring Devices: Status Assessment
CS-3914 Final Report (RP2300-1); $13.00
Contractor: Battelle, New England Marine Research Laboratory
EPRI Project Managers: W. Chow, M. Miller

Proceedings: Workshop on Sampling and Analysis of Utility Pollutants
CS-3921 Proceedings (RP1851-1); $19.00
Contractor: TRW, Inc.
EPRI Project Manager: W. Chow

Assessment of Ash-Sluice-System Operating Problems
CS-3923 Final Report (RP1260-44); $26.50
Contractor: Radian Corp.
EPRI Project Manager: W. Micheletti

Coal-Waste Artificial Reef Program
CS-3936 Final Report (RP1341-1); $14.50
Contractor: New York State Energy Research and Development Authority
EPRI Project Manager: D. Golden

Manual for Investigation and Correction of Boiler Tube Failures
CS-3945 Final Report (RP1890-1); $40.00
Contractor: Southwest Research Institute
EPRI Project Manager: B. Dooley

ELECTRICAL SYSTEMS

Electrical Systems Catalog
EL-3600-SR; $10.00
EPRI Project Manager: J. Marks

Detection of Electric Meter Tampering
EL-3951 Final Report (RP1779-1); $11.50
Contractor: Honeywell, Inc.
EPRI Project Manager: H. Songster

Field Evaluation of 69-kV Outdoor Polysil Insulators
EL-3961 Final Report (RP1281-6); $8.50
Contractor: Pennsylvania Power & Light Co.
EPRI Project Manager: J. Dunlap

ENERGY ANALYSIS AND ENVIRONMENT

External Quality Assurance for the Plume Model Validation and Development Project: Moderately Complex Terrain Site
EA-3761 Final Report (RP1616-10); $13.00
Contractor: Research Triangle Institute
EPRI Project Manager: G. Hilst

Proceedings, Indoor Air Quality Seminar: Implications for Electric Utility Conservation Programs
EA/EM-3824 Proceedings (RP2034-10); $23.50
Contractors: William I. Whiddon and Associates; Hart, McMurphy and Parks, Inc.
EPRI Project Managers: R. Patterson, G. Purcell

Evaluation of Published Studies Analyzing the Association of Carcinogenesis With Exposure to Magnetic Fields
EA-3904 Final Report (RP1824-3); $10.00
Contractor: H. Daniel Roth Associates, Inc.
EPRI Project Manager: R. Patterson

ENERGY MANAGEMENT AND UTILIZATION

Electricity and Industrial Productivity: A Technical and Economic Perspective
EM-3640 Final Report (RP1201-17, TPS81-797)
Contractor: Philip S. Schmidt
EPRI Project Managers: L. Harry, R. Mauro, T. Schneider

1983 Utility Cogeneration Survey
EM-3943 Final Report (RP1940-3); $11.50
Contractor: Synergic Resources Corp.
EPRI Project Manager: D. Hu

Small-Hydropower Development: The Process, Pitfalls, and Experience
EM-4036 Interim Report (RP1745-15); Vol. 1, $46.00; Vol. 2, $13.00
Contractor: Morrison-Knudsen Engineers, Inc.
EPRI Project Manager: C. Sullivan

NUCLEAR POWER

BWR Full Integral Simulation Test (FIST) Facility: Description
NP-2314 Interim Report (RP495-1); $23.50
Contractor: General Electric Co.
EPRI Project Manager: S. Kalra

Effectiveness of Thermal Ignition Devices in Lean Hydrogen-Air-Steam Mixtures
NP-2956 Final Report (RP1932-14); $14.50
Contractor: Atomic Energy of Canada Ltd.
EPRI Project Manager: J. Haugh

BWR Full Integral Simulation Test: Phase 1 Results
NP-3602 Interim Report (RP495-1); $23.50
Contractor: General Electric Co.
EPRI Project Manager: S. Kalra

Field Test and Evaluation of Electropolishing and Preoxidation Processes for Type-316 Stainless Steel Nuclear-Grade Piping
NP-3832 Final Report (RP2296-5, -6); $16.00
Contractors: Quadrex Corp.; General Electric Co.
EPRI Project Manger: C. Wood

Analytical Description of PWR Pressurizer Transients
NP-3850 Final Report (RP443-3); $13.00
Contractor: Dartmouth College
EPRI Project Manager: J. Sursock

Analytic Simulator Qualification Methodology
NP-3873 Interim Report (RP2054-1); $20.50
Contractor: Babcock & Wilcox Co.
EPRI Project Manager: J. Sursock

High-Amplitude Dynamic Tests of Prototypical Nuclear Piping Systems
NP-3916 Final Report (RP964-9); $14.50
Contractor: Anco Engineers, Inc.
EPRI Project Manager: Y. Tang

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