The Macroelectronics Revolution

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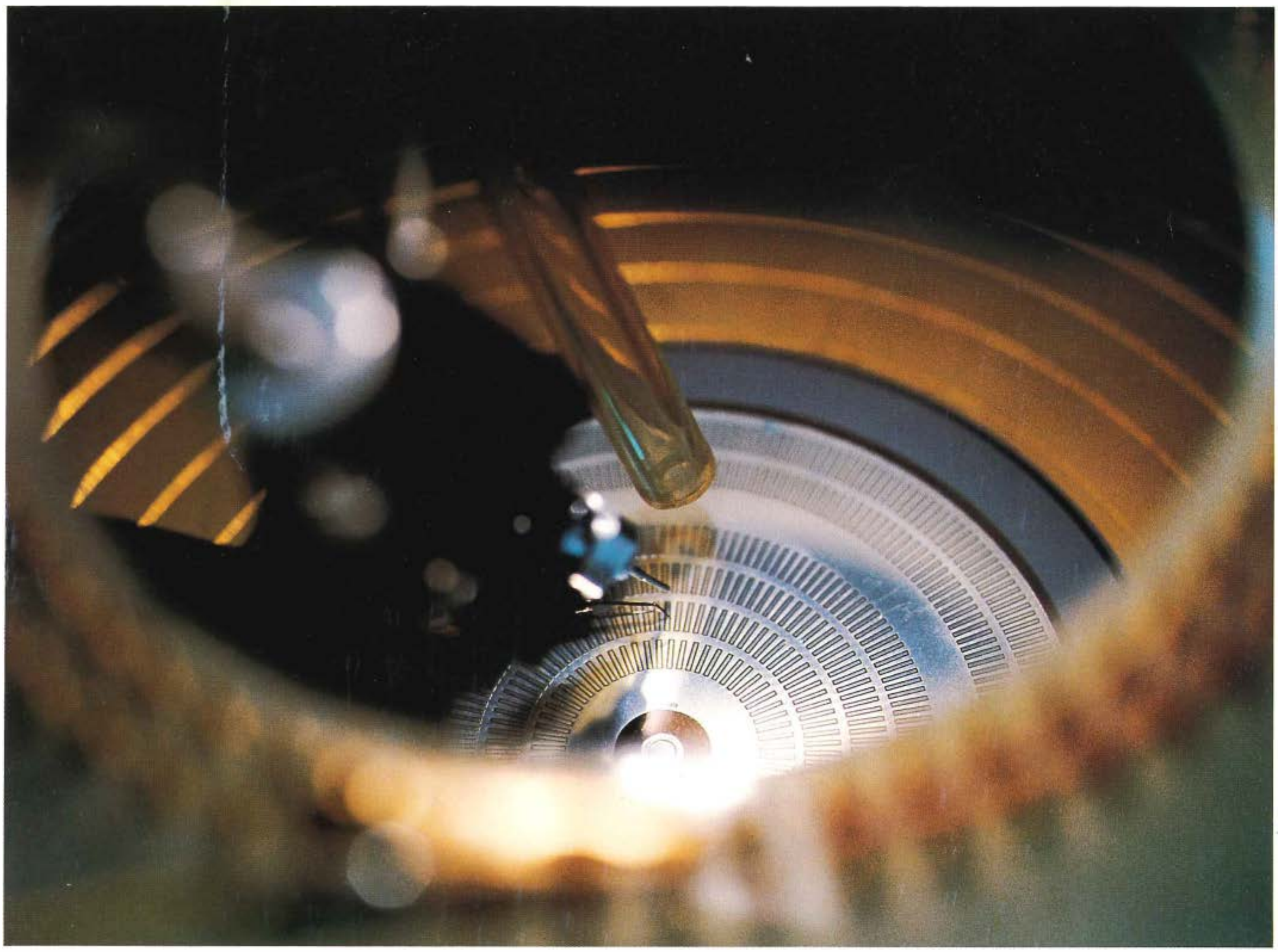

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Cover: Automatic testing of a 5000-V, 2500-A gate turnoff thyristor wafer. Such state-of-the-art power electronics devices are expected to revolutionize the handling of bulk electric power.

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Power Electronics: A National Priority

Hingorani

Electric utilities and many of the manufacturing industries they serve are on the threshold of revolutionary change brought about by high-power electronics. Over the last two decades the increasingly dense integration of low-voltage, low-current circuits on small silicon chips has transformed office equipment and communications networks. During the next two decades the development of semiconductor devices for high-voltage, high-current applications will bring about an equally fundamental transformation in major industrial equipment and utility networks.

This second electronics revolution has already begun, as this month's *Journal* cover story makes clear. Power electronics is now being used to make ac/dc converters for high-voltage dc (HVDC) transmission, static VAR compensators, uninterruptible power supplies to protect sensitive equipment, and drives for adjustable-speed motors. In the near future, power semiconductor devices are expected to make the electricity generated by photovoltaic and wind facilities more easily compatible with utility transmission networks, and over the longer term, these devices may even replace mechanical switches on distribution power lines.

An ominous shadow has been cast, however, over this otherwise optimistic picture. Power electronic devices are constructed from silicon material that must meet even more demanding standards than that used in integrated circuit chips. At present there is no commercial source of this material in the United States. Further, efforts by American companies to incorporate available power semiconductor technology into industrial equipment now lag behind progress made by foreign competitors.

For more than 12 years EPRI has sponsored pioneering research on power electronics, with particular emphasis on applications that benefit electric utilities. A light-fired thyristor developed with EPRI funding is now lowering the cost and increasing the reliability of equipment used in HVDC converters. Our recently established Power Electronics Applications Center (PEAC) should help speed the introduction of efficient new technology into industrial applications, and other EPRI work with power semiconductors promises to hasten utilization of solar and wind energy resources.

Acting alone, however, neither EPRI nor any other individual research organization with a vital interest in power electronics can meet all the current R&D needs. The only way we can successfully be at the leading edge in power electronics is for various funding organizations to coordinate their research to avoid duplication of effort and to establish synergistic lines of inquiry. EPRI is willing to play a major role in this coordinated effort, for we believe that development of power electronics deserves to be treated as a leading national priority.

Narain G. Hingorani
Vice President
Electrical Systems Division

Authors and Articles


Mehta


Ferraro


Goodman


Schneider


Dooley

Sealed in Silicon: The Power Electronics Revolution (page 4) surveys R&D to scale up semiconductor materials and packaging for use at high power levels in electric utility and other industrial systems. Written by John Douglas, science writer, aided by research managers from three EPRI divisions.

Harshad Mehta is a project manager in the Electrical Systems Division who has special expertise in semiconductor technology. Mehta came to EPRI in 1983 from the R&D Division of Fairchild Semiconductor Corp., where he worked in device research for two years after earning a PhD PhD in electrical engineering at the University of Florida. He has BS and MS degrees in physics from Vikram University in India.

Narain Hingorani, director of the Electrical Systems Division and an EPRI vice president, was named to his position in May 1986, after three years as director of the Transmission Department and nine years as a program manager. He came to EPRI in 1974 from the Bonneville Power Administration, where he worked for six years, much of the time on the high-voltage dc intertie between Oregon and California. Hingorani graduated in electrical engineering from the University of Baroda (India) and earned MS and PhD degrees at the University of Manchester (England).

Ralph Ferraro manages the Industrial Program in EPRI's Energy Management and Utilization Division. Between 1977 and 1984 he headed research in power electronics. Before coming to EPRI, Ferraro worked for four years with Bechtel Power Corp. as design supervisor for power plant control and instrumentation systems. Still earlier, he worked in the design and production of power conversion and control equipment. Ferraro has a BS in electrical engineering from the New Jersey Institute of Technology.

Frank Goodman, a project manager in the Advanced Power Systems Division since 1979, is responsible for circuit protection and control provisions for solar-electric technologies. Much of his work has been with windpower systems. Goodman formerly worked for the Los Angeles Dept. of Water & Power for four years. He holds BS, MS, and PhD degrees in electrical engineering from the University of California at Santa Barbara. ■

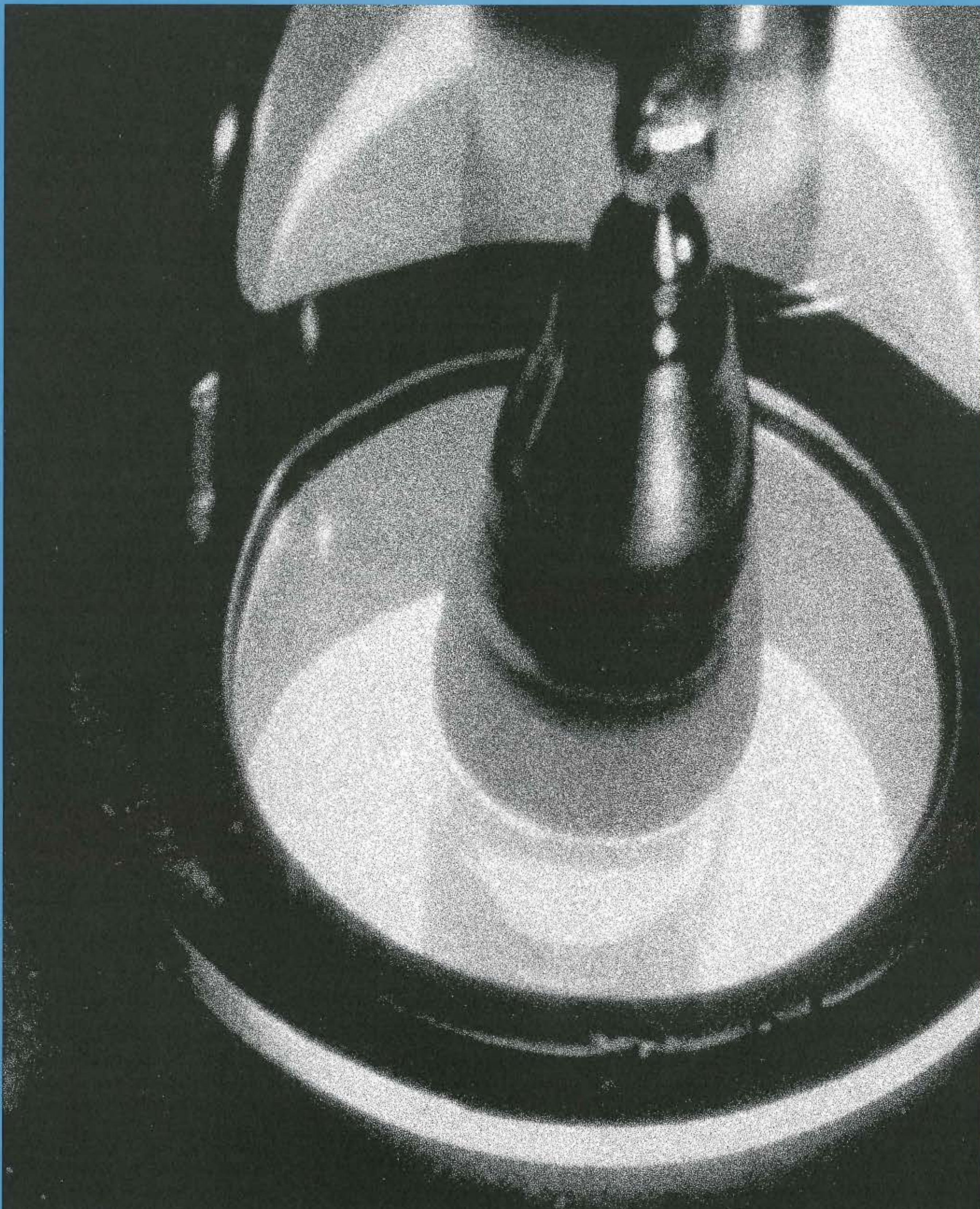
Lighting and the Human Condition (page 16) discusses wide-ranging research into the qualities and properties of illumination that can affect human health and capabilities. Written by Michael Shepard, *Journal* feature writer, with information from a cooperating research center.

Thomas Schneider has been president of the Lighting Research Institute, an industry-based nonprofit research management organization, since October of 1985. He was formerly with EPRI for more than eight years, becoming department director for research in energy utilization and conservation technologies. Schneider's early career was as a research physicist for Public Service Electric & Gas Co. in New Jersey. He has a BS from Stevens Institute of Technology and a PhD in physics from the University of Pennsylvania. ■

Anne Carter on the Impact of Technology Change (page 24) presents an economist and EPRI Advisory Council member who is disturbed by the social outcome when technology's benefits and costs fall to different groups. Written by Ralph Whitaker, feature editor of the *Journal*, who interviewed Carter during a recent meeting of the Council. ■

Winning the Fight Against Boiler Tube Failure (page 32) introduces a new EPRI manual for correcting the basic causes of boiler tube failures, not just for patching the leaks themselves. Written by Jon Cohen, science writer, with assistance from staff in the Coal Combustion Systems Division.

Barry Dooley, an EPRI project manager since July 1984, is responsible for research on boilers and auxiliaries, with special emphasis on measures to extend plant life. He was formerly with Ontario Hydro for nine years, eventually as supervisor of the chemistry and metallurgy department. Before 1975 he was in the materials division of the Central Electricity Research Laboratories in England. Dooley graduated in engineering metallurgy from the University of Liverpool and earned a PhD in metallurgy there. ■



Development of power electronics—solid-state technology for the efficient handling of bulk electric power—stands at the point where integrated circuits did 30 years ago. Like their microelectronic counterparts, power electronics devices are expected to have a revolutionary effect, changing forever the way that we generate, deliver, and use electricity.

SEALED IN SILICON
THE POWER ELECTRONICS REVOLUTION

It has been called the second electronics revolution—the application of advanced semiconductor technology to high-voltage, high-current tasks in utility networks, industrial processes, and home appliances. The advantages of speed, reliability, and efficiency that integrated circuits on silicon chips brought at the microwatt level to computers are now being used to control megawatt transmission networks through power electronics.

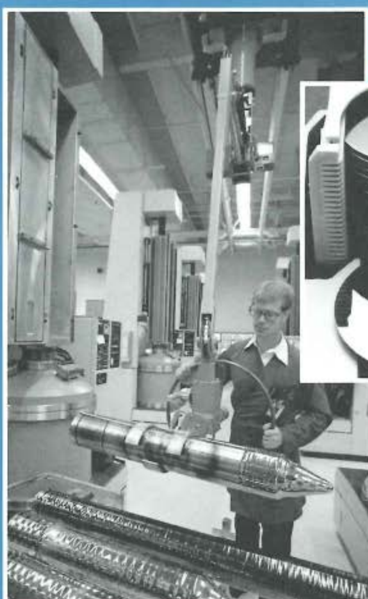
In the simplest terms, solid-state electronics devices, both large and small, gain advantages of speed and low energy loss by whisking current through alternate layers of silicon with different conducting properties. In integrated circuits, individual devices, such as diodes and transistors, are microscopic. In power electronics equipment, a single switching device called a thyristor is constructed from four silicon layers that may be 4 in (102 mm) in diameter for high-current applications. Sealed in a modular package, such a device can weigh 5 lb (2.3 kg). Equipment like a transmission line ac/dc converter may consist of hundreds of thyristors arranged in approximately 50-ft (15-m) stacks. Just as integrated circuits replaced vacuum tubes in radios, thyristors have already replaced expensive, inefficient mercury arc tubes in ac/dc converters and may someday be able to replace mechanical circuit breakers on distribution lines.

The full impact of power electronics devices is just beginning to be felt, for they are constantly finding new applications ranging from adjustable speed for motors to industrial heating controls. "Within about two decades," predicts Narain Hingorani, vice president, Electrical Systems Division, "all electricity will flow through several power semiconductor stages between generation and consumption."

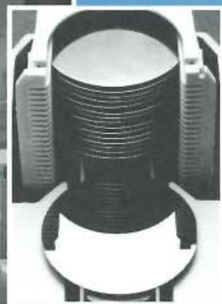
Concern is rising, however, that the United States is falling behind overseas competitors in the development and use of power electronics. The pure, defect-free, high-resistivity, single-crystal silicon required for power semiconductors is not now commercially available from a domestic source. Several important areas of R&D related to the design and packaging of high-power devices are lagging because of insufficient research funds. And some technology already available is not being fully utilized because equipment manufacturers are often unaware of the advantages power electronics offers for

Fabricating the Thyristor

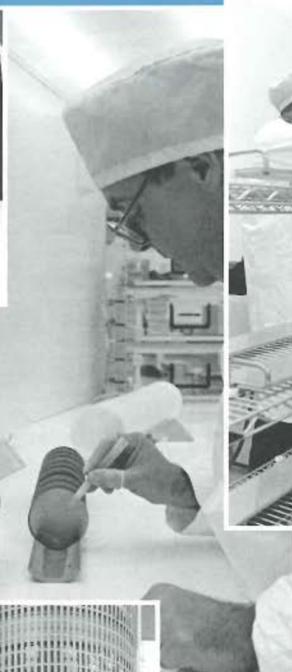
After the single-crystal silicon ingot is pulled, it is cleaned, rounded, and sliced into wafers. The wafers are placed in diffusion chambers and doped with specific impurities to create discrete layers that have the desired conductive properties. Patterns are then etched into the wafer surface in a series of steps and metalized to form electrical connections within the silicon. Finally, the wafer is packaged with contacts, buffer materials, and a ceramic housing to form the finished thyristor—a module about an inch high and four inches in diameter.



Crystal growth



Slicing



Wafer loading

Diffusion

Photolithographing

Alloy plating

Gold plating

Assembly

lowering capital costs and improving productivity and energy efficiency.

ELECTRIC UTILITIES probably have the most at stake in the international competition over power electronics. Within the utility industry itself, power semiconductor devices are revolutionizing control and conversion of bulk electricity. Greater use of power electronics in industry could also benefit utilities by improving load efficiency and increasing market penetration of new electrotechnologies.

For the last 12 years EPRI has sponsored pioneering research on advanced power semiconductor devices for utility application. This research has helped establish U.S. leadership in specific areas of power electronics technology and has led to a dramatic increase in the use of power semiconductors in some key transmission operations. Further progress, however, will require closer coordination of increasingly expensive research by producers of semiconductor materials, equipment manufacturers and users, government organizations, and the utility industry. EPRI is now helping to establish such a coordinated national research effort, which will be unprecedented in its scope and potential effect on a very fragmented area of high technology.

Research on power electronics can be roughly divided into three broad areas: semiconductor materials, devices and packaging, and applications. At EPRI the Electrical Systems Division is responsible for R&D on semiconductor materials, advanced devices, and applications related to high-voltage dc (HVDC) and other transmission and distribution areas. Applications of power semiconductor devices to industrial and commercial equipment and systems is handled by the Energy Management and Utilization Division; the Advanced Power Systems Division evaluates new materials for solar photovoltaic energy conversion and is developing power electronics controls to improve wind turbine generators and battery storage systems.

The challenge of materials

Materials research is fundamental because device options are limited by the properties of the semiconductors from which they are made, and materials costs are leveraged through production of highly value-added electronic systems. (In 1985 worldwide consumption of all electronic materials was $2.4 billion, which supported an equipment market estimated at $388 billion.) Because of this leverage, the rapid erosion of an early U.S. lead in materials technology has caused mounting concern. A national workshop sponsored by the Federation of Materials Societies recently stated, "The loss of a competitive electronic materials base inevitably leads to a loss in competitiveness in the manufacture of circuits and systems." So rapidly is technology changing, the group concluded "if the current trend continues, it can be anticipated that the United States will be a minor force in the world market in electronic materials and systems by the early 1990s."

This conclusion applies particularly to the special semiconductor materials needed for high-power electronics devices. The single-crystal silicon used in the manufacture of integrated circuits represents some of the purest material ever produced, but it still contains too many impurities to withstand the strain of high voltages and currents. Most of this quality material is produced in ingots with a diameter of 3–5 in (76–127 mm) drawn vertically from the surface of molten silicon in a quartz crucible. The problem with this Czochralski (CZ) method is that oxygen and other impurities from the crucible are incorporated into the silicon crystal structure.

Currently, all the silicon for power electronics is produced by a float zone (FZ) method, which does not involve a crucible. Instead, a rod of polycrystalline silicon is suspended in a radiofrequency field, which melts its lower portion and allows a single-crystal ingot to be drawn downward with very little contamination. The problem is that the FZ process for producing silicon ingots, which are sliced into wafers for device manufacture, is much more expensive than the CZ method. Also, the only commercial FZ facilities are outside the United States—one in West Germany and two in Japan. These manufacturers give preference to their domestic buyers of power semiconductor material, so the lead time for filling orders for the United States and other countries can be as long as 60 weeks.

EPRI has recently granted two manufacturing licenses and associated R&D contracts for producing power-quality silicon in an effort to lower costs and advance the silicon ingot technology available in the United States. Cybeq, a division of Siltec Corp., received a license and contract to explore the feasibility of improving the quality of silicon produced by the CZ method by surrounding the crucible with an intense magnetic field. The presence of a field greatly slows the migration of impurity ions through the silicon melt. If successful, this magnetic CZ process should reduce the cost of power-quality silicon by 15–20%, compared with using the conventional FZ method. At the same time Westinghouse Electric Corp. will explore ways of improving the FZ process and making it less expensive. Total savings for the utility industry from these programs are expected to run $30 million a year by 1995.

Devices and packaging

The usefulness of solid-state electronics devices stems from their ability to shift the flow of electricity in response to very subtle changes inside their semiconductor material. Because of their advantages in handling high currents, thyristors have become the workhorse of power electronics. EPRI work has focused on reducing the cost of thyristors, increasing their versatility, and lowering the energy losses that occur in these important devices.

One important breakthrough occurred in 1983 with the first commercial demonstration of a light-fired thyristor developed by General Electric Co. and Westinghouse in cooperation with EPRI. Use of light greatly reduces the energy needed to turn on the thyristor and reduces overall system cost because less auxiliary equipment is necessary. During the successful EPRI-sponsored demonstration, a combination of electrically triggered and separate, light-fired thyristors were part of the HVDC module installed at the southern end of the Pacific Intertie line, the country's largest HVDC transmission system. Development of the light-fired thyristor is expected to have significant impact in the near future on lowering the cost and increasing the reliability of HVDC converter valves.

A nagging problem since thyristors were first developed has been the need to reverse line polarity before they can be turned off. One solution has been to develop a gate turn-off (GTO) thyristor by rearranging the device configuration so the gate is nearer the negative (cathode) end of the device. When a negative voltage is connected to the gate the thyristor turns off, enabling it to serve as a two-way power switch. Such a capability can considerably widen the applications in which thyristors are used, and EPRI is involved in both cost reduction research on GTOs and efforts to demonstrate their potential benefits. Recently, a contract was issued to General Electric to use the most advanced 3-in-diam (77-mm) GTOs now commercially available as the basis for the power conditioning system in Southern California Edison Co.'s new battery energy storage facility.

The main disadvantage of GTOs is the large gate current needed to turn them off. Over the long term, a more promising technology appears to be the so-called MOS-controlled thyristor, or MCT. (MOS stands for metal oxide semiconductor and refers to the arrangement of components in devices based on this technology. Many integrated circuits requiring very low energy loss, such as those in watches, are based on MOS technology.)

An MCT would consist essentially of an MOS integrated circuit created on the top surface of a high-power thyristor. In such a device a very large line current could be switched off by a much smaller gate current. In addition, MCTs have a turn-off time less than one-third that of GTOs. Considerable R&D still has to be conducted on MCTs, however, before their full potential can be reached. This work includes raising the voltage and current capacity, improving circuit density and device yield through better fabrication, and introducing new package concepts. General Electric recently received a license to manufacture a high-power MCT developed through EPRI funding.

THE ISSUE OF DEVICE PACKAGING arises frequently in discussions of research still needed on all kinds of power semiconductor devices. The basic reason is that present devices generally use a large tungsten or molybdenum contact plate to transfer current from a silicon wafer at the heart of a device to the rest of a high-power circuit. If a contact plate made of silicon could be used, the cost and weight of power thyristors would be greatly reduced. The challenge to using silicon contact plates is that they have more resistance and less ability to conduct heat than does metal. These and other research concerns are being addressed through EPRI contracts with General Electric and Powerex, Inc. (a power semiconductor joint venture company owned by General Electric, Westinghouse, and Mitsubishi).

"The revolution in power electronics is being driven by the need to lower costs, increase efficiencies, and conserve energy," explains Harshad Mehta, Electrical Systems Division project manager. "Power semiconductors are already proving their worth in a variety of utility applications, including HVDC transmission, static VAR compensators, subsynchronous resonance damping, and adjustable-speed motor drives. If EPRI's work on materials technology and advanced devices is successful, the use of power electronics in utility-related applications should expand dramatically over the next few years. This will be particularly true if our research on MCTs pays off because this technology has the potential for replacing most of the devices in use today."

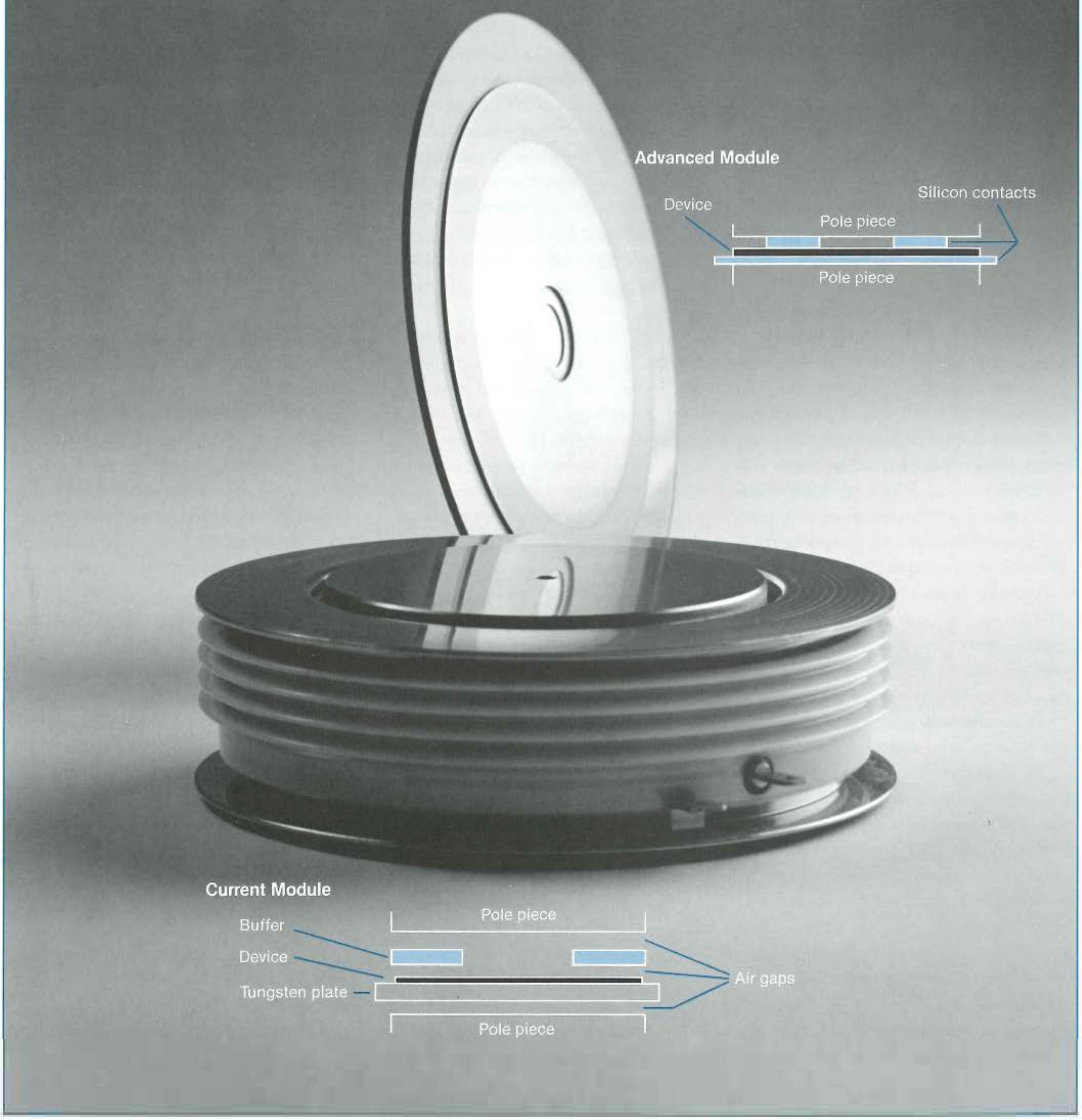
Opportunities for application

Power electronics also has great potential to reduce costs and improve the efficiency of a wide variety of industrial and commercial technologies that depend on electricity. Devices already developed can cut the cost of adjustable-speed drives, power supplies, power line conditioners, and other equipment by 50% or more. Properly integrated into such equipment, power semiconductors may contribute a 20% overall savings in capital costs of some equipment for industrial processes. Such savings could help lower manufacturing costs and increase industrial productivity, benefiting utilities by increasing load retention and efficiency, as well as by supporting load compatibility and growth.

Many industrial energy users and process equipment manufacturers, however, are unaware of the opportunities provided by power electronics. In addition, many of the power semi-

The Module of the Future

For high-power applications, a semiconductor device, such as a thyristor, must be packaged in modular, easily stacked units. Today's thyristor (foreground) includes a thick, heavy tungsten plate to disperse heat and form a contact with the bottom of the device. EPRI researchers developing the next generation of thyristor packaging hope to use silicon contacts that can be soldered directly to the copper pole pieces with no need for air gaps. The resulting module (mockup, background) would be not much thicker than the silicon wafer itself. Although silicon has more resistance to current flow and less ability to remove heat than does tungsten, successful development of silicon contacts could greatly reduce the weight and cost of high-power thyristors.



Inside Power Electronics

By itself, a large, pure crystal of silicon does not conduct electricity very well, but it can be made conductive by doping with controlled amounts of appropriate elements that either give or take away electrons from the crystal lattice. An n-type semiconductor has been doped with phosphorus or other elements that donate free electrons to the crystal. A p-type semiconductor has been doped with boron or some other element that takes electrons away from silicon atoms in the crystal, creating positively charged holes that move through the lattice.

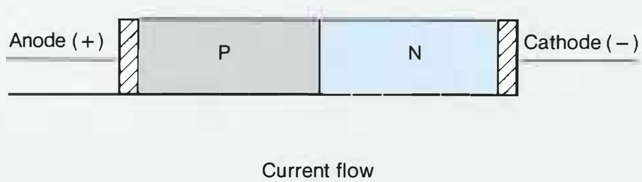
The junction between layers of n-type and p-type material will conduct electricity only when the electrons and holes are brought together from opposite sides, as when a positive voltage is imposed on the p-side and a negative voltage on the n-side, a condition known as forward bias. When the bias is reversed, current ordinarily will not flow across the junction. (Conventionally, current is drawn as the flow of positive charges.) A single p-n junction can thus act as a rectifier because it will pass current only during the positive half of each cycle in response to alternating voltage.

For most high-power applications, however, thyristors are constructed from four different layers of silicon in an n-p-n-p configuration, which will conduct current when positive voltages of different magnitudes are imposed on the two p-layers. Applying a positive voltage to the gate layer forces holes to the junctions of the neighboring n-layers. The presence of a positive potential on the gate allows a thyristor to be turned on at any point in a positive cycle.

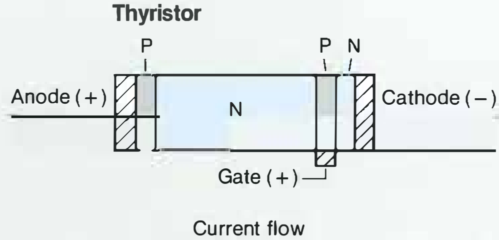
Once the thyristor is turned on, it continues to conduct current (even when the gate potential is removed) until the voltage polarity on the cathode and anode is reversed. For a thyristor to be used as a two-way switch, however, it must be able to turn the current off or on anywhere in the appropriate cycle. In a GTO thyristor, this is done by rearranging the silicon configuration so that the gate is interdigitated between multiple cathodes at one end of the device. Ordinarily, current flows to the cathode, which is connected to a small n-region embedded in the adjacent p-layer. When a negative voltage is connected to the gate, however, current is drawn away from the cathode to the gate itself, and the thyristor turns off.

To reduce the gate current in the turn-off mode, a new generation of thyristors is being designed using MOS technology. The basic principle underlying MOS devices is that a current can pass between two n-type semiconductors if electrons are attracted to the surface of a p-type strip between them by a positive potential on an adjacent metal gate. Such operation requires very little gate current, and MOS circuits can be packed very densely on the surface of silicon chips. An MOS-controlled thyristor has such a configuration on top of the silicon layers that form the main part of the thyristor. When the MOS gate is made positive, current is sidetracked, and the device turns off. □

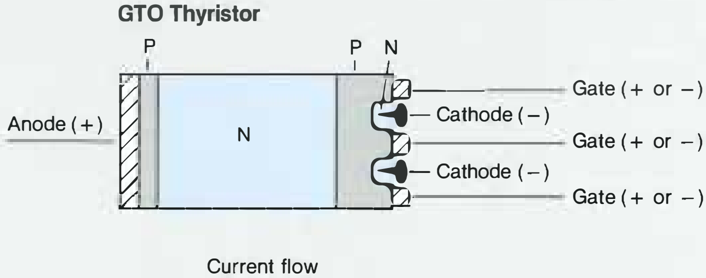
Diode



Thyristor



GTO Thyristor



conductor devices now in use have been imported. Changes in the critical market for motors with electronic adjustable-speed drive (ASD) are symptomatic. Since 1980, while total sales have risen steadily, the market for domestically produced ASD equipment has actually declined and the value of imports has more than tripled. United States industry is now considered to be somewhat behind other countries in the exploitation of power electronics.

To increase the awareness and understanding of power electronics technologies and issues, EPRI recently established the Power Electronics Applications R&D Center (PEAC) in Knoxville, Tennessee. The center will be a focal point for applications research on power electronics equipment and for transferring related technologies to the commercial sector. PEAC will be run under contract by the Tennessee Center for Research and Development, with staff and facilities support from the University of Tennessee, Knoxville, the Tennessee Valley Authority, Martin Marietta Energy Systems, Electrotek Concepts, Inc., and the state of Tennessee. More than two dozen other organizations, including several major corporations, have also pledged their support.

One of the first tasks to be undertaken at PEAC will be a thorough assessment of currently available power electronics technologies in order to define specifications for new equipment, systems, and applications. PEAC will relate these specifications to advances in component and device technology and develop collaborative R&D programs with industries to integrate these advances into commercial equipment. Specific R&D projects will be launched to improve the use of power electronics in selected applications, such as uninterruptible power supplies, active powerline conditioners, process control and energy management systems, and adjustable-speed drives. These projects will be cofunded by the industries most likely to benefit.

"Our emphasis at PEAC will be two-way communication with the technology users and the technology creators," comments Ralph Ferraro, program manager in the Energy Management and Utilization Division. "The potential applications are almost endless: Adjustable-speed drives can save 30–50% of the energy wasted in some industrial processes; new power control systems can allow broader use of inexpensive ac motors in the residential, commercial, and transportation sectors; and someday you may even have a microwave dryer for home laundry. Power electronics provides the lever to introduce all sorts of new electrotechnologies into the economy."

POWER ELECTRONICS may also help pave the way for generating electricity from renewable resources. One of the most significant potential advances in wind turbine technology, for example, is variable-speed generation through power electronics control. Because of shifting wind velocities, the present generation of constant-speed turbines cannot always deliver the maximum amount of energy and can send power fluctuations onto utility lines. A wind turbine controlled by power electronics could provide a more optimal match to wind velocity, thus improving energy capture by 15–20%. In addition, this next generation of wind turbines would feature simplified blade control, less physical stress on structural elements, reduced wear on drive trains, and improved compatibility with the utility networks.

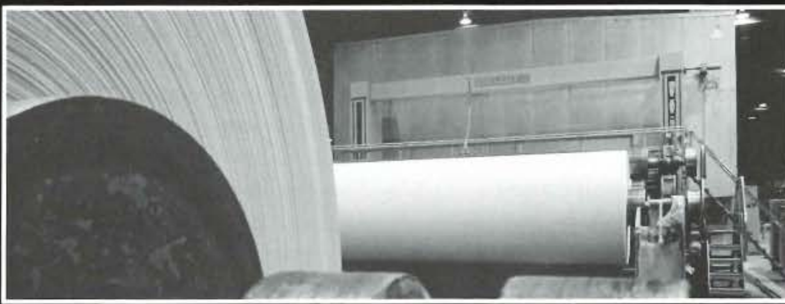
The present challenge is to reduce the cost of the power conversion system needed for such turbines, which is still relatively expensive. With the use of new concepts, the cost of the power electronics may be reduced by half. To bring this about, EPRI is establishing a cooperative research program with U.S. Windpower, Inc. (and perhaps individual utilities) focused on development of a wind turbine controlled by power electronics and optimized for utility use. The program would begin with a 12-month feasibility study, followed by a development program that would result in construction of prototype turbines. Specific goals of the program are to clarify the role of power electronics in wind power and to develop wind generating units that could be fully integrated as components of a utility system. These units could mitigate some of the adverse electrical behavior of present wind generators and could be automated for remote data acquisition and real-time dispatch from a central control point.

In the area of solar photovoltaics, EPRI research on power electronics should bring two major benefits. First, the low-cost, high-purity silicon materials needed for power semiconductors may also meet the requirements of high-efficiency photovoltaic cells with suitable adaptations. (Impurities or defects lower the efficiency of photovoltaic energy conversion.) Second, the power-conditioning systems that connect photovoltaic units to a utility network can be greatly improved through the use of advanced power semiconductor devices. In the past, power conditioning systems have required addition of corrective filters containing expensive copper and iron. Advanced solid-state devices could reduce filtering requirements, as well as the physical size, weight, and cost of power-conditioning systems. At present, high-power thyristors appear to be the best candidates for constructing such systems, but by 1990, GTOs and MCTs are expected to become competitive and help further reduce the amount of control hardware.

"Many options are open to us as we

Putting Power Electronics to Work

Applications for power semiconductor devices are expected to proliferate in the coming decade, both inside and outside the utility industry. Huge thyristor valves are at the heart of utility HVDC transmission facilities, and smaller modules will be used for circuit protection and in power conversion equipment for battery storage systems, wind power machines, solar cells, and other power technologies. The next generation of electric transportation systems will need similar conversion and control equipment. Power electronics devices are now moving into basic industrial processes, such as induction heating and melting for steelmaking and advanced separation processes in the chemical industry. In addition, electronic adjustable-speed drives improve the performance of motor-driven systems for manufacturing, for elevators and escalators in commercial buildings, and for pumping and irrigation equipment in agriculture and wastewater treatment applications. Even residential appliances will eventually include power semiconductors as Smart House concepts focus on more-flexible control of household electricity use.

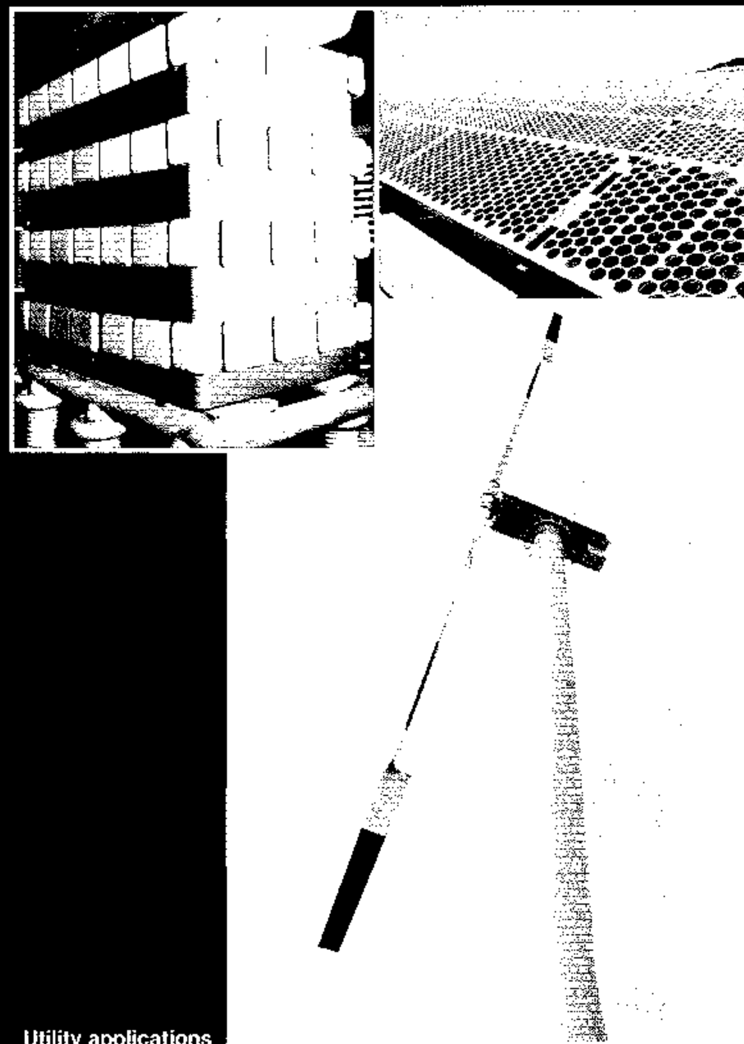


Industrial processes and manufacturing

Electric transportation

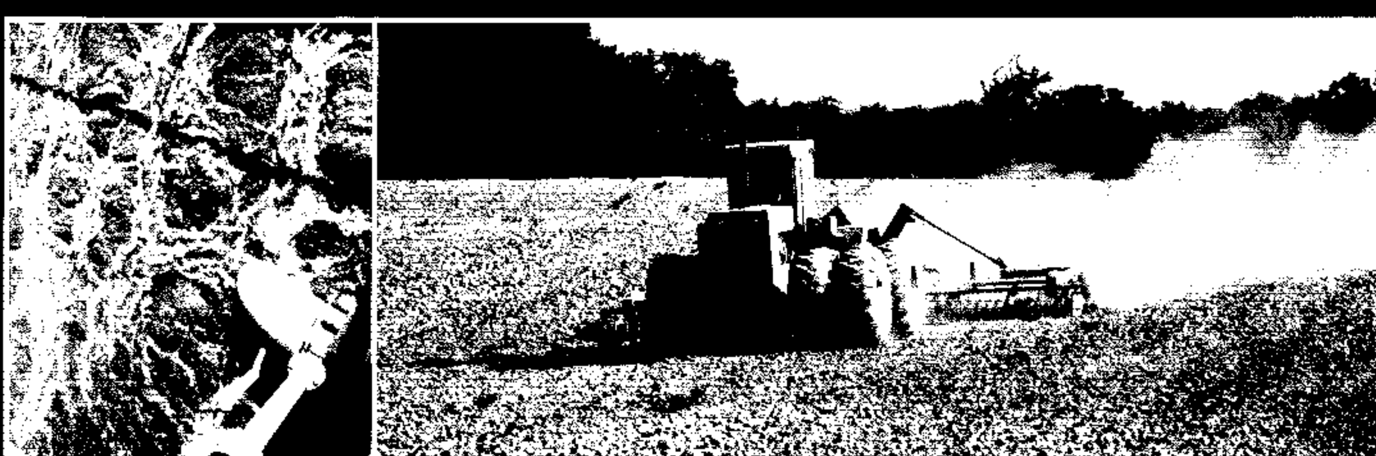
Household appliances

Commercial buildings



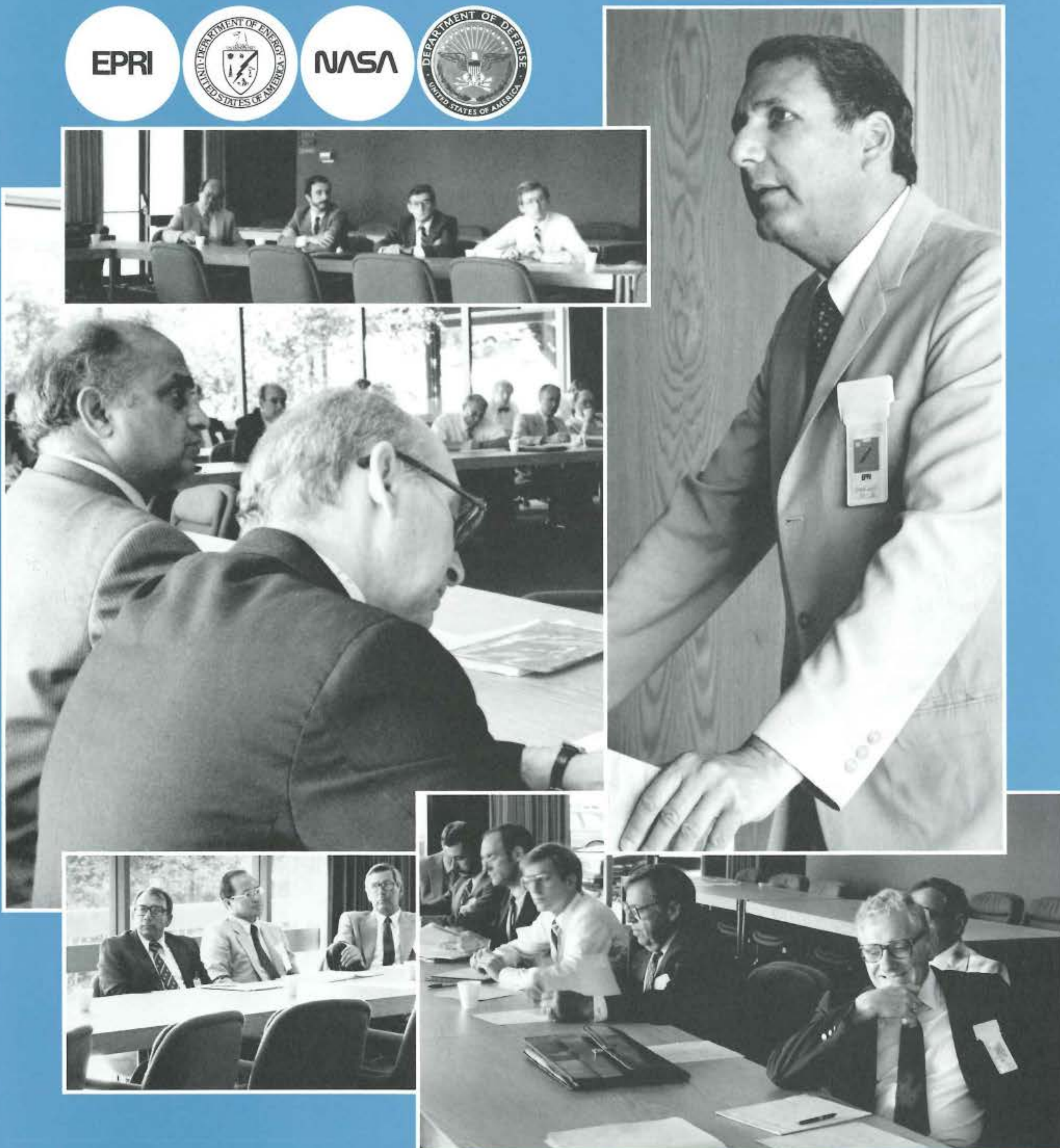
Utility applications

Waste treatment and agriculture



National Cooperation

The Ad Hoc Interagency-Utility Group on Power Semiconductor Switches and Materials was founded in January 1986 at a workshop hosted by the Electronics Technology and Devices Laboratory of Fort Monmouth, New Jersey. The group, which includes experts from EPRI, DOE, NASA, and DOD, brings together leaders in the power electronics field to coordinate research activities, share information, identify applications, and discuss requirements for the future of power semiconductors.



develop these new systems," says Frank Goodman, Advanced Power Systems Division project manager. "The most cost-effective devices for power conditioning in solar and wind facilities have not yet been identified. The research now getting under way should help clear up the issues and eventually result in renewable energy facilities that better meet utility needs. In addition, the materials research now being aimed at improving power semiconductor devices will certainly help meet the requirements of high-efficiency photovoltaic cells as well. Advances in power electronics are definitely improving the prospects for both solar and wind energy."

Developing a national approach

As research on improved semiconductor materials, advanced power electronics devices, and new applications has progressed, there has been a growing realization among various funding organizations that the task is too great to be handled individually, particularly if aspiring to be at the leading edge in power electronics technology. For this reason unprecedented meetings were held in Asbury Park, New Jersey, in January 1986 and then at EPRI in Palo Alto, California, in July to bring together the leaders in power electronics for exploratory talks on coordinating their research. EPRI was one of the organizers and sponsors of this workshop, which included participants from government, industry, and the university community.

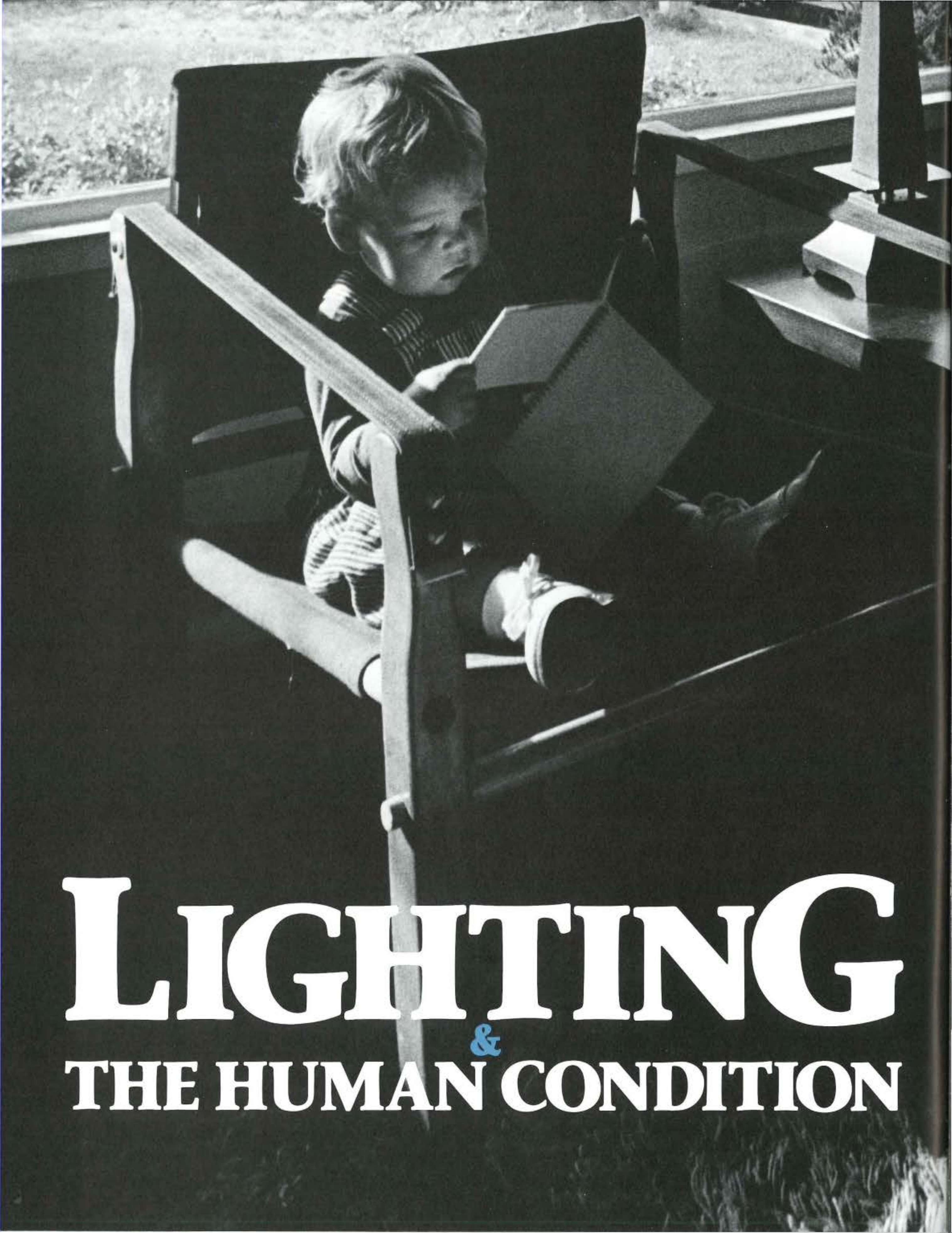
Out of the workshop came tentative, informal agreement on research priorities, coordination of funding to avoid unnecessary duplication of effort, broad sharing of results, and the possibility of even closer cooperation through jointly funded programs in the future. Over the next five years, approximately $20 million will be needed for materials research and $40 million for development of improved devices. EPRI is expected to play a leading role in those programs of most use to utilities, subject to the availability of funds. Interviews with other workshop participants reveal some of the ways that sharing responsibility for various research efforts can benefit all the parties involved.

TO THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA), power electronics represents a critical opportunity to decrease payload weight. "Power electronics is a building block technology for all types of spacecraft and aircraft," comments Gale Sundberg of the NASA Lewis Research Center. "We've proposed a power electronics system for an all-electric airplane, for example. Using such a system could take 10% off the empty weight of a plane and save a corresponding 10% on fuel." In such a craft, electric motors, rather than a hydraulic system, would move wing flaps and the tail assembly. Studies for a proposed space station also indicate that a power management and distribution system based on advanced power semiconductors would weigh 40% less than alternative concepts—a particularly important factor considering that thousands of dollars are required to lift each pound of equipment into orbit. Because by themselves these applications are not large enough to generate a market for particular kinds of power semiconductor devices, Sundberg emphasizes the "synergism of all our needs" with the whole spectrum of research conducted by other organizations.

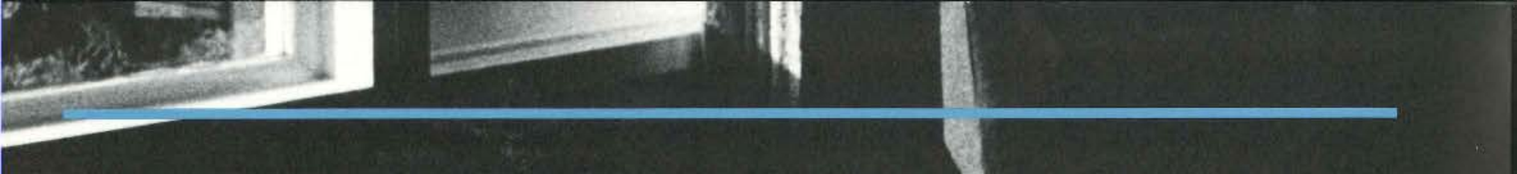
Similar sentiments are echoed by Stephen Levy of the U.S. Army's Electronics Technology and Device Laboratory. "The reason it's so important to share experiences and costs is that neither the government nor industry can generate the required research money alone. This has to be a cooperative venture. All sides will profit. Most of the basic devices we are working on can ultimately be used by utilities or their major customers." As an example, Levy cites the possibility of storing energy in large superconducting coils in addition to batteries. Mechanical switching of current would be impossible in this case because of arcing, so such a storage system (useful to the army because of its light weight) would require switching by power semiconductors.

"EPRI is basically providing seed money to support development of light-fired thyristors, GTOs, and MOS-controlled thyristors," concludes Hingorani. "We cannot afford, however, to fund all the research that could eventually lead to devices of interest to the utility industry. Our priorities are very different from those of NASA and the Department of Defense, but there are clearly a large number of areas where sharing results of coordinated research could be very helpful. Again I want to emphasize the importance of leverage—although power semiconductor devices may represent a small fraction of the total cost of a utility installation, they can help save much larger fractions of total capital costs by enabling improvements in the remainder of a plant. My concern is that we are in danger of losing this leverage to other countries. R&D in power electronics requires and deserves a coordinated national approach." ■

This article was written by John Douglas, science writer. Technical background information was provided by Narain Hingorani and Harshad Mehta, Electrical Systems Division; Ralph Ferraro, Energy Management and Utilization Division; and Frank Goodman, Advanced Power Systems Division.



LIGHTING & THE HUMAN CONDITION



Should energy efficiency be the primary concern in lighting the human environment? Emerging research indicates that the quality of our lighting can have subtle but powerful influences on how we work, feel, and function.

Ever since Thomas Edison first hung out his shingle, much of the market for electricity has been to provide light. Today, nearly one quarter of the electricity sold in the United States is devoted to this end use. In the dozen years since the energy crisis appeared, considerable attention has been given to improving the efficiency of lighting. Impressive gains have already been made in lighting efficiency, and it is widely acknowledged that further advances could double the efficiency with which we use electricity for illumination.

Many lighting designers suggest, however, that the overall efficiency of lighting systems cannot be measured solely in watts per square meter but should also consider aspects of lighting quality like color rendition, contrast, glare, and new insights that are now emerging on the biologic and psychologic effects of light. Research conducted in the last few years has revealed a number of mechanisms by which light affects our productivity, health, biologic rhythms, moods, and general sense of well-being.

The brightness and timing of light, for instance, affects hormonal flows that synchronize our internal biologic clocks. Certain kinds of light are implicated as potential causes of retinal damage, cataracts, and skin cancer and as cures for jaundice in new-borns, mood disorders, and vitamin D deficiency. The spectral distribution of light sources and their color rendition affect visual fatigue, the way the eye focuses, and the accuracy and speed with which certain tasks can be performed.

Much of the research in this area is in its early stages and is raising more questions than answers. Is there an optimal amount of light for task performance? for minimizing fatigue? for keeping spirits high? Are particular wavelengths better for us than others? Which is healthier—daylight or electric light? A lot more research will be needed before these issues can be resolved, but it is clear already that this rapidly emerging branch of inquiry may have important implications throughout society.

Light and the rhythms of life

Scientists have identified four key parameters that influence light's effect on living systems: intensity, duration, timing, and spectral distribution. Each of these parameters appears to influence such biologic rhythms as sleeping, wakefulness, feeding, and body temperature in humans, as well as in other animals. One key mechanism in this internal clockwork is the secretion during periods of darkness of a hormone called melatonin by the pineal gland, located in the brain.

Researchers have long known that light suppresses melatonin secretion in lower animals, such as frogs, whose pineal glands are close enough to the surface of their skin to respond directly to changing light levels. But the pineal glands of larger animals, including man, are located too deep in the brain to be directly sensitive to ambient light levels. Because early laboratory experiments failed to demonstrate that light could suppress melatonin secretion in humans, many scientists came to believe that people's internal clocks were regulated by something other than light.

This view changed in 1980 when researchers found that illumination five times brighter than ordinary room light—although still considerably dimmer than typical midsummer daylight—would suppress melatonin secretion in humans. This finding in itself was of considerable scientific interest, but it also raised a host of questions about the biologic effects of electric lighting systems. If typical indoor lighting levels are too dim to trigger the hormonal changes that synchronize our internal clocks, what are the implications for people who spend most of their time indoors? And if light is a key ingredient in synchronizing our body rhythms, what other as yet poorly understood effects might it have on our health, productivity, moods, and energy levels?

One of the first applications to arise from the new understanding of light's role in hormonal balance came in the treatment of people suffering from a form of wintertime depression known as seasonal affective disorder. Because many of these patients come out of their funk as the days grow longer in spring, psychiatrists reasoned that their symptoms may be related to reduced light levels in winter. Alfred Lewy of Oregon Health Science University has conducted experiments clearly demonstrating that one week of exposure to bright morning light produced significant improvement in patients suffering from winter depression. This work confirmed the hypothesis that the patients' depression was due to phase-delayed circadian rhythms.

Scientists are just beginning to explore whether light therapy can help people experiencing other kinds of sleep and mood disorders. Likely candidates include workers who change shifts often, insomniacs, and travelers trying to fend off jet lag.

Lighting and Health

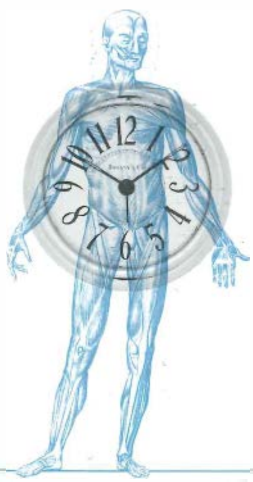
Light has positive and negative health effects. Ultraviolet light causes sunburn, skin cancer, retinal damage, and cataracts but also stimulates the production of vitamin D and causes suntan, which protects the skin. Light treatments are used regularly to cure jaundice in newborns and to relieve chronic winter depression caused by dissynchronization under low wintertime light levels of the hormonal flows that regulate biologic rhythms. Such rhythms influence sleep-and-wake cycles, energy levels, and hunger. In addition to the small numbers of people suffering from severe light-related depression, there may be many more individuals who experience subclinical effects, such as changes in mood and energy levels, as a result of the lighting regimes they are exposed to.

Causing eye damage

Treating depression

Treating neonatal jaundice

Synchronizing biologic rhythms



Producing vitamin D

Causing sunburn

Although light treatment does help some individuals with relatively rare and severe dissynchronization of their internal clocks, there are not enough data yet to say how the general population is affected by the lighting they are now exposed to. "However," comments Thomas Schneider, president of the Lighting Research Institute (LRI), "this work does raise interesting questions about the contribution light makes to well-being and productivity in the general public."

Light and health

In addition to influencing hormonal processes, light can affect us through other mechanisms. It is common knowledge, for instance, that ultraviolet (UV) rays in sunlight have both positive and negative effects. They can cause sunburn and cellular changes that may lead to certain forms of skin cancer. This issue is particularly timely because of the reported degradation of the UV-filtering ozone layer in the upper atmosphere. There is also evidence that UV radiation can cause cataracts and retinal damage in the eye.

Because fluorescent lights produce some UV radiation, concern has been raised that this form of indoor lighting may be unhealthy. This concern is heightened by the fact that interest in energy efficiency is leading to increased use of fluorescent lights and new fixture designs that do not use UV absorbing plastic diffusers.

This issue received some publicity in 1982 when an epidemiologic study conducted in Australia found a correlation between past exposure to fluorescent light and skin cancer. Other studies have found no such link. "If such a relationship does exist, the implications for indoor lighting could be significant," comments Schneider, "but it is too early for any conclusions to be drawn because the evidence gathered thus far is incomplete and inconsistent." LRI is now funding a project designed to check the Australian study and to overcome flaws in the original experimental design.

To further explore this question, LRI also funded a study in which hairless mice of a strain known to be very vulnerable to skin cancer were exposed over an extended period to a combination of fluorescent light and high levels of UV light from a separate source. The experiment was designed to simulate conditions of exposure to bright sun and indoor electric lighting. No increase in cancer from the fluorescent exposure was detected over the levels induced by the sunlight-simulating sources.

Lighting manufacturers maintain that the UV light issue can be resolved if necessary by using UV filters in fixtures or by making changes in lamp design that would reduce the output of bulbs in the UV portion of the spectrum.

Such changes should be approached cautiously, however, because there is also evidence that UV rays can have some beneficial effects. Although they cause sunburn, lower exposures lead to suntan, which can be beneficial because the tanning process arises with the formation of a skin pigment called melanin that absorbs UV radiation and keeps it from penetrating deeper into the skin.

UV light also has the beneficial effect of triggering the chemical process that leads to vitamin D production in the skin. Despite the fact that many of our foods are fortified with vitamin D, certain populations, particularly the elderly, are often deficient in this important nutrient, which is critical for calcium absorption. One study of elderly veterans found that their ability to absorb calcium fell by 25% during the winter. A similar group exposed to fluorescent light showed a 15% increase in calcium absorption.

Neonatal jaundice, which affects more than 10% of premature babies, in extreme cases can cause brain damage and other harm if not treated promptly. In the past, some infants born with jaundice were given blood transfusions, a very risky treatment for newborns. But thanks to an observant British nurse who noticed that babies whose cribs were near windows showed a lower frequency of jaundice, doctors now routinely use light treatments to safely and inexpensively cure the syndrome within several days. Laboratory studies have shown that the blue wavelengths are most effective in combating the illness.

Light and productivity

Although light clearly has a role in both causing and curing certain biologic effects, far more research will be needed to understand the links between light and productivity in the general population. Part of the difficulty lies in measuring productivity and identifying the key parameters that affect it.

Despite the complexities involved in quantifying the relationship between productivity and light, it is an important question that a number of experiments have tackled in the past. Recent studies in this area, conducted by Mark Rea of the National Research Council of Canada, have shown that the speed and accuracy with which subjects performed different reading-writing tasks were strongly affected by luminous contrasts between white paper and inks of varying darkness.

Emerging research is showing, however, that other visual functions, including pupil dilation and contraction, adaptation to high contrast (important in such applications as viewing video display terminals), and the ability to distinguish colors, are all affected by the spectrum of the light source.

Samuel Berman of the Lawrence Berkeley Laboratory and Donald Jewett of the University of California Medical Center are conducting research on how light spectrum affects pupil size. Their findings show that light sources with different spectrums but identical intensity will cause different amounts of pupil dilation or contraction. Pupil size is important because it affects the eye's depth of field, much like the aperture or *f*-stop of a camera lens. Some tasks, like precision watch making or small-component assembly, require good depth of field. Berman and Jewett's work indicates that spectral control of pupil size may be a key element in

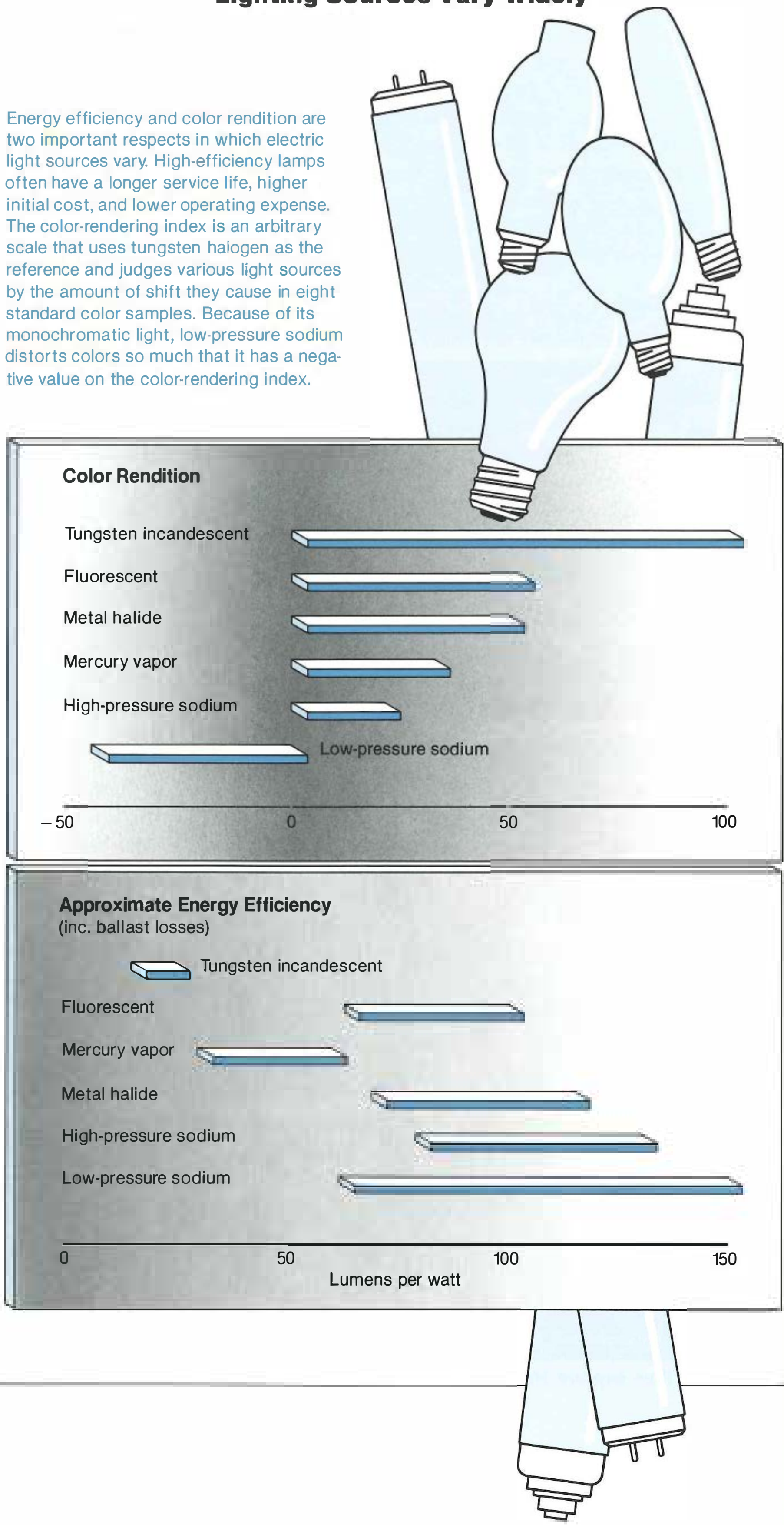
Lighting Sources Vary Widely

Electric lamps can be divided into three principal groups: incandescent, fluorescent, and high-intensity discharge, a category that includes mercury vapor, metal halide, high-pressure sodium (HPS), and low-pressure sodium (LPS) lamps. The light from these sources varies in spectral distribution and color rendition, and the lamps themselves differ in efficiency and service life. All but the incandescent bulbs require a ballast to transform incoming voltage and current to levels the lamps need. Ballasts range widely in efficiency and are a major factor in the total energy use of light sources. High-efficiency solid-state ballasts, for instance, have led to a generation of fluorescent lights 35% more efficient than conventional fluorescents.

Incandescent bulbs, popular in most homes, use electricity to heat a tungsten filament until it glows. This is the least efficient kind of light source. Only 10% of the energy radiated by the filament is visible light. The rest is heat radiation in the infrared portion of the spectrum. Because most of the visible light emitted by incandescents is in the yellow and red wavelengths, many perceive this source as being warm and soft.

Fluorescent lamps are standard in most office buildings because of their long life and high efficiency (four or more times that of incandescents). The fluorescent lamp requires a ballast to produce an electric arc in the tube. This arc generates UV radiation, which causes a phosphor coating on the inside surface of the lamp to glow, releasing light. Manufacturers can

Energy efficiency and color rendition are two important respects in which electric light sources vary. High-efficiency lamps often have a longer service life, higher initial cost, and lower operating expense. The color-rendering index is an arbitrary scale that uses tungsten halogen as the reference and judges various light sources by the amount of shift they cause in eight standard color samples. Because of its monochromatic light, low-pressure sodium distorts colors so much that it has a negative value on the color-rendering index.



vary the spectrum of fluorescent light by adjusting the chemical mixture of the phosphor coating.

The way high-intensity-discharge lamps work is by sending an electric arc through a vaporized metal, such as mercury, metal halide, or sodium. These lamps take several minutes to come up to full output, and once turned off must cool to a given temperature before they can be turned on again.

LPS lamps are the most efficient bulbs available, but they produce a monochromatic yellow light that has poor color rendition. LPS lamps are used primarily for street lighting and other applications where color is not important. HPS lamps have somewhat better color rendition than their low-pressure counterparts, but they are slightly less efficient. Also used in streetlighting, HPS units are now being applied in some commercial, industrial, and institutional settings.

Metal halide lamps are used in a variety of applications from indoor display lighting to stadium floodlighting. They have good color rendition and, although less efficient than sodium sources, are more efficient than mercury vapor and many fluorescent lamps.

Mercury vapor lamps have been used widely in industrial and outdoor lighting because of their low cost and long life. Mercury lamps with phosphor coatings on the inside bulb surface have moderate color rendition and are starting to be used in lobbies, hallways, retail areas, and other interior applications. They are not as efficient as most fluorescents. □

Elements of Lighting Quality

Productive work requires light appropriate to the task or setting. The right amount of light is critical—too little or too much light causes eyestrain and fatigue. Light should accentuate contrast so the eye can clearly distinguish key objects from their background. Good color rendition is vital in some situations, such as medical examinations, where skin color carries clues to physical condition. The direction of lighting is also important to provide balance and to avoid shadows or glare. All these elements contribute to overall lighting quality, which plays a key role in how people function in and appreciate a space.

Contrast

Color


Quantity


Direction

optimizing visual performance.

In addition to affecting depth of field, pupil size influences how much of the lens area is used to focus an image. The larger the pupil, the more of the lens is used, accentuating visual distortion for those with impaired vision.

The spectrum of a light source influences more than pupil dimension and depth of field, however. It also affects the ability to perceive color differences, a feature that is more important in some settings than in others. In art galleries, for instance, lighting must allow viewers to accurately perceive colors. In streetlighting, on the other hand, drivers are typically less concerned with color rendition than with seeing the road, other cars, and any obstructions that may be in their path. Consequently, many roadways are now lit with high-pressure sodium (HPS) lamps because they provide good illumination of the kind drivers need and they are energy-efficient. These lamps produce a yellowish light with poor color rendition, however. To ensure that safety is not compromised, new paints have been developed to give stop signs and other traffic markers good color rendition under HPS lighting.

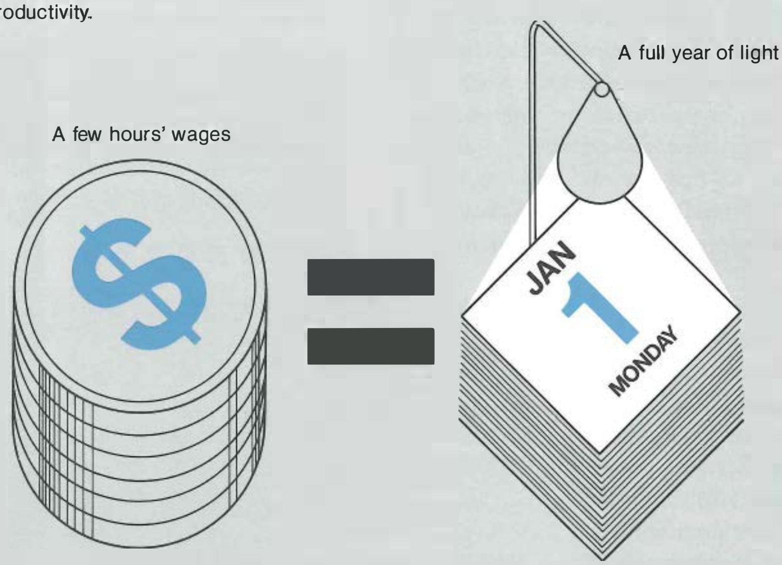
In some cases a preoccupation with energy conservation has led building designers to inappropriately install HPS lamps in settings where color rendition is critical. Doctors and nurses in a newly constructed medical facility in New England found that they could not judge the patients' skin and tongue color under HPS lamps. And the operators of an employee cafeteria in Georgia found that workers were avoiding the facility because the lighting made the food appear unpalatable. In both cases the problems were corrected by replacing the sodium lamps with light sources that have better color rendition.

Balancing efficiency and quality

The examples of the medical facility and the cafeteria illustrate a debate that has been under way among lighting professionals for some time. The debate hinges

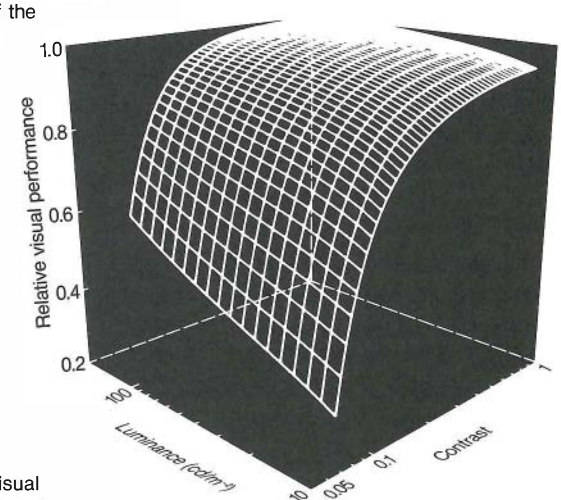
Balancing Efficiency and Quality

The trend toward increasingly stringent energy efficiency standards for lighting is fueling a debate. Some designers believe that lighting quality and, in turn, productivity will suffer if we require too much energy conservation in lighting. They point out that light is a relatively small cost of doing business (a few hours of a worker's wages equals the cost of lighting his workspace for an entire year) and that even small reductions in productivity caused by inferior lighting will outweigh the savings in energy costs. Proponents of stricter standards believe that with improved technology and better design we can have lighting that is both efficient and high in quality, with no sacrifice in productivity.



Quantifying Visual Performance

Researchers are exploring ways to measure the relationship between productivity and lighting quality. Mark Rea of the National Research Council of Canada has developed a three-dimensional quantitative model depicting visual performance as a function of luminance (brightness) and lighting contrast. The model shows that visual performance is best under high luminance and high contrast, declines gradually through an intermediate range of values, and then falls off sharply as luminance and/or contrast are constrained below certain threshold levels. Because visual performance is a key ingredient in productivity, such models can help designers create more effective working environments.



on how far we can pursue energy efficiency in lighting systems without sacrificing color rendition, contrast, glare, and other aspects of lighting quality.

Every state building code now includes limits on the amount of energy to be used for lighting in nonresidential buildings. Lighting efficiency standards have become consistently more stringent since energy concerns first rose high on the national agenda in the 1970s. They have contributed to improvements in lighting efficency that are already saving at least $1 billion/yr.

Although significant gains in lighting efficiency have already been made, advances in technology continue to make further efficiency improvements possible. A new set of proposed lighting standards has been under development and review for the past three years by the American Society of Heating, Refrigeration, and Air Conditioning Engineers; the American National Standards Institute; and the Illuminating Engineering Society. According to William Fischer, who heads a committee working on the new rules, the standards as now drafted will be twice as stringent, on average, as those in force a decade ago.

Some lighting designers, like Hayden McKay of Howard Brandston Lighting Design, Inc., believe that the new proposed standards may go too far. "The attempt to minimize rather than to optimize energy has become so severe that in some cases it seriously threatens the quality of the lighting environments and the effective use of those spaces," she says. McKay supports the goal of energy conservation and maintains that well-trained lighting designers can create high-quality lighting that meets the proposed efficiency standards. She is concerned, however, that many of the individuals specifying lighting systems for the building industry do not have the background needed to design good lighting within the narrow tolerances the new standards will create. "Education must go hand in hand with standards," she says. "Otherwise we are going to see a lot of poorly lit spaces."

McKay points out that lighting is a relatively small portion of a business's expenses. The cost of lighting a typical employee's workspace for an entire year, for instance, equals a few hours of the worker's wages. But light is an important ingredient in worker productivity, and even a small reduction in lighting quality may create productivity losses that outweigh the savings from energy efficiency gains.

Mark Rea concurs. He has developed a quantitative model that measures visual performance as a function of two key parameters: luminance (brightness) and contrast. Although good lighting solutions can be obtained with varying combinations of these essential ingredients, Rea maintains that subtle changes in the mix can lead to small changes in visual performance that may, in turn, impair or enhance productivity. Moreover, visual performance drops off sharply if one parameter (such as luminance, which depends in part on energy use) is constrained too rigidly.

Stephen Selkowitz, who heads the Windows and Daylighting Program at Lawrence Berkeley Laboratory, maintains that the new proposed standards are not overly stringent. He believes that better interior use of daylight from the sun and sky would give designers additional options in creating high-quality lighting that is also efficient. "Daylighting strategies could be employed as part of an overall integrated lighting and building design strategy to reduce building energy consumption 50% below the values that are achieved today."

Selkowitz acknowledges that daylighting cannot solve all lighting problems. He cautions that the successful designer must understand the benefits and limitations of each design strategy and then select those that are best suited for the specific application at hand. Despite these caveats, he remains confident that daylighting techniques and high-efficiency lighting are getting better and will have an increasingly important role to play in the future. "As designers become more sophisticated and skilled," he predicts, "energy efficiency and lighting quality will increasingly come to be perceived as complementary rather than conflicting goals."

The debate over lighting energy standards is likely to continue for some time, and to grow more complex as we learn more about the myriad ways in which light affects us. Schneider observes, "It is entirely possible that lighting designs that are optimized not just for visual acuity and energy efficiency but for health, mood, and productivity as well could be very different from the approaches that we now consider state of the art. It is too early to say what these developments could mean in the future for utilities, but it is clear that as the prime supplier of lighting energy, the electric power industry has a key role to play in this exciting and important new branch of investigation." ■

Further reading

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This article was written by Michael Shepard. Technical background information was provided by Thomas Schneider, Lighting Research Institute.

ANNE CARTER ON THE IMPACT OF TECHNOLOGY CHANGE

Anne Carter joined EPRI's Advisory Council only a year ago. But far-reaching connections are already forming in her mind. "I begin to get a vision for EPRI," she says, "that EPRI is the R&D arm of an industry that's basic to all other industry. In a way, EPRI's agenda could appropriately shape the research agenda for the whole country. And I'm not sure," she adds as a contemplative afterthought, "I'm not sure EPRI wants to be in that position."

Carter speaks with a particular fascination for industrial technology and its influences throughout society. She has been a professor of economics at Brandeis University for 15 years, and before that she was a longtime research associate at the Harvard (University) Economic Research Project, ultimately its director of research.

As an Advisory Council member, she joins 20 or more men and women who are EPRI's window to the world outside the electric utility industry—individuals drawn from academia, law, conservation, science, industry, regulation, medicine, labor, and other commercial, civic, and consumer groups. But most of all, Carter is a student (and has been since her undergraduate days at Queens College) of the impact of technology change.

"Part of the drag on productivity in our economy is that a lot of people are rendered unproductive just when others are rendered more productive."

That is what stimulates her observation about EPRI. She is always on the lookout for technology's bellwether or, better yet, its prime mover—the instrumentality that gives it direction and might somehow deal more equitably with the costs of technology change, the fact that change itself renders a lot of things obsolete.

"Our system is a great engine for change," Carter explains, "precisely because it concentrates its rewards on successful innovators and lets the costs fall elsewhere." Then she adds a reflective note. "Whether that's fair or not depends on the extent to which the overall benefits ultimately accrue to the losers as well as to the winners."

Why be an economist?

Carter was introduced to technology change and its aftermaths when she was only five or six years old. Her family lived in New York City, where her father had manufactured automobile accessories since the early 1920s—first "wind deflectors" and then, when windshields became standard equipment, windshield wipers. But as the Great Depression deepened, Detroit made the next logical move, and cars began to come off the line with wipers in place. It was a technology change that the family business could not survive.

Carter's childhood memories are therefore mixed. Success had taken the family in 1929 to Forest Hills, a Long Island suburb beyond the subway, but failure of her father's company threatened their new home. "I had $65 in the Lincoln Savings Bank," Carter recalls, "built up by bringing my dollar to school every week. And then my mother said, 'We're going to take your $65. We need it.' This is the end, I thought. They have taken my nest egg."

Carter stops short of moralizing. "I'm not saying that we should stop change, but we have to be aware of the costs. Part of the drag on productivity in our economy is that a lot of people are rendered unproductive just when others are rendered more productive.

"And it isn't just an economic thing. I saw my father change from the man of the house to the failure of the house."

In recent years Carter has come to realize that the societal impact of technology change has "haunted me all my life. I'm not the economist's economist," she insists, "and I went through much of my life wondering why I was in economics, feeling I had backed into it."

Indeed, her choice of economics as a college major still appears to have been serendipitous. In quick succession Carter considered premedical study and physics, and just as quickly she ran up against the family and societal values expressed by her parents and advisers: A doctor? Don't you want to have children? Physics? Women don't do that! Why don't you be a teacher? Eventually, as Carter tells it, she made appointments to consult with the heads of the Queens College psychology and economics departments; however, "The head of the psych department didn't show up."

Even after Carter's 1945 graduation (summa cum laude) from Queens at 19, there were extraprofessional criteria for what to do next. "I was idealistic, I identified with the downtrodden, and I had a job lined up with a labor union in Chicago," she reminisces, "but I was reminded that I didn't know anyone there. And besides, I always got homesick."

But Carter had three clear reasons for graduate study at Harvard: acceptance, a scholarship, and a boyfriend already there. The next four years included course work and research toward a 1949 PhD in economics from Harvard's Radcliffe College and two years back in New York City as an instructor at Brooklyn College. But most of all, the period at

Harvard was when she met Wassily Leontief, the professor of economics who became her thesis adviser and mentor. She would work for him and with him, off and on, for 30 years, until the late 1970s.

Input-output analysis

Leontief, a Russian emigré, had been in the United States and at Harvard since 1931, conceiving what we know in economics today as input-output (I–O) analysis. He elaborated his innovation in a 1940 book, *The Structure of the American Economy,* and has continued his specialization ever since, honored for this work with the 1973 Nobel prize for economics.

I–O analysis is an empirically based method, and Leontief's personal style as champion has done much to set it in sharp opposition to the traditional, theoretical methods. Mainstream economic analysis assumes price to be the dominant variable in supply-demand relationships. I–O analysis gives primacy to technologic factors, which create strong linkages among industrial sectors. Because a new technology changes the inputs that one sector purchases from other sectors (not to mention the outputs it sells), any change produces a ripple effect throughout the various industries of the economy. Cost and price relationships change accordingly.

I–O analysis has proliferated in part because computers make it possible to compile and manipulate elaborate data bases, which today involve hundreds of sectors in models of the U.S. economy. Most other nations also have I–O tables, which are linked by several world models. "Electric power is a relatively easy industry to study," Carter observes, "because it's so well documented. Actually, there are two such industries; the other is textiles," she adds, recalling her earliest work for Leontief, a pilot study on the diffusion of new technology and its effects on that industry.

In retrospect, it is clear why I–O analysis appealed to Carter. It dealt with her then-unacknowledged personal agenda. "How can economic change produce miracles for some and heartache for others?" The years of work have been rewarding, both for her and for the maturation of I–O analysis. But as for that ultimate question, she still has not found a complete answer. "No, I don't have policy prescriptions to help society minimize the costs of change, of obsolescence. If we loaded those costs on innovators alone, we'd discourage change and lose its benefits entirely."

Overall, industry is paying much of the cost of technology change today, Carter notes. "We wonder that our industrial productivity statistics don't show more improvement, but we're not distinguishing between capacity expansion and capacity replacement. Even when the intent is to expand, doing it with new technology usually means replacing some old technology and," she adds pointedly, "the people associated with it. Productivity figures record the net result."

At least tentatively, Carter accepts the image of a private sector that innovates and a public sector that normalizes many of the consequences—that is, reimburses those economic, geographic, or demographic sectors that bear costs of change without sharing significant benefits. "I believe a generous safety net is essential," she says, speaking of allowances for worker retraining, relocation, early retirement parachutes, and the like.

In Carter's view, electric utilities have simultaneous potential for being winners and losers in the process of technology change. She points to what she calls regional economic volatility in the United States, "part of my 'who's paying the cost?' problem," she says, as some regions prosper and others decline. On the downside, utilities can lose their most important customers, and they have no control over that.

"A utility in the rust belt can't move to the Sunbelt any more than housing and schools can follow the workers. . . . Neither employers nor employees are safe."

"When that happens," Carter adds on a bleak note, "a utility in the rust belt can't move to the Sunbelt any more than housing and schools can follow the workers. But," she adds, "the idea of one class exploiting another isn't the point here. Neither employees nor employers are safe."

Family and career moves

Carter's Harvard years were also family years. Married in 1953, she had a son in 1955 and a daughter in 1959. "Those were years when it was okay to stay home and be a mommy," she says with a smile. "When Frank was born, I was ready to be captain of the station wagon and revel in the whole business!" This experience almost, but not quite, edged out economic research.

"I remember Wassily's saying we had to talk," Carter continues. "We had croissants and coffee, and he said things like, 'You'll regret it. . . . Just name your terms. . . . You can work half a day a week. . . . Do a little of this and a little of that, but stick with it; don't just give it up.'"

An engaging, insistent, and contentious man, Leontief prevailed, but Carter maintained only a pro forma research connection between 1955 and 1959. "My heart was somewhere else," she concedes, and she goes on to speak of her own unfolding perception as she matured during the 1950s and as she watched her children grow during the 1960s.

"Until I was 20, the world had seemed very fragile to me. Whatever happened, could happen to me, personally. By the time Frank was born, I was getting used to the idea that the world wasn't so fragile after all. But the Cuban missile crisis, and again when Kennedy was shot—both times we were watching on TV, and the feeling rushed back: it's fragile."

The TV itself elicits irony from Carter. "That's partly why I remember so well. We don't watch TV very much, only when the world is coming to an end!" By the time of the moon landing in 1969, she recalls, the TV was upstairs.

Throughout her years at Harvard, Carter focused much more on research than on teaching. Even when she was appointed an assistant professor in 1966, there was a clear message that research publication would continue to mean more to her career and to the university. Carter the economist had no quarrel with this; Carter the professional woman did. "In those days," she says, with an implication of ancient history, "the way to a professorship was to teach at a women's college." The irony was that she had been an assistant professor at Smith College 15 years earlier and had taught both before and since at Brooklyn College and at Wellesley.

Faculty tenure eluded Carter at Harvard. As Leontief's director of research at the Economic Research Project after 1968, she had, in her words, only industrial tenure. She looked elsewhere, was a visiting professor at Brandeis in 1971–1972, and accepted a faculty appointment there the following year.

A year or two later, then a full professor, Carter herself invoked the value of her research in turning down a deanship. "I had a large NSF grant, and the university would have been losing money for me to accept the new academic post." Not until 1981 would Carter feel "ready for an adventure, ready for a break, ready to do something different." Even so, she laughs as she remembers

"I decided to quit being a dean and return to economics. I have some ideas I want to develop. . . . Technology obsolescence, however intractable, is still 'my' problem."

"Some of us are putting ourselves in EPRI's shoes and thinking, 'The world is changing very fast, and we're in a strategic position. There's a loose ball; we can grab it and run with it.'"

her exchange with the Brandeis president when he asked her to be dean of the faculty.

"My first impulse was, 'I don't *do* that!' Then I said I'd like to think about it." Three days later, still thinking about it, she concluded that she must want the position. "If not, I would have turned it down already. So I said yes."

Of that decision process and the five years that followed, Carter remarks, "I felt I had never been terribly decisive. Here was my chance to learn how to be definite, even tough if I needed to be." She learned at least two things about decisions, along with getting tougher. One was, "Sometimes the alternatives are awfully close, and it really doesn't much matter, so you just decide."

Carter also learned that she was more decisive than she had acknowledged. There is a lot that happens to us that we do not choose—an economist would call them exogenous variables—but we choose our responses to them, deliberately or not. Carter came to realize how and why she had chosen her responses to the economics department head who kept his appointment back at Queens College, to the acceptance letter from Harvard, to the query from Leontief about a pilot study of textile industry technology, to his later plea that she stay in professional touch, and to the opportunity for academic fulfillment at Brandeis.

"And after five years," Carter says with some finality, "I decided to quit being a dean and return to economics. I have some ideas I want to develop," she adds; then she sharpens her focus. "I realize that technology obsolescence, however intractable, is still 'my' problem."

Advising on strategic issues

Carter's research has increasingly engaged her in energy assessments and analyses, notably the development of a world model for the United Nations in the early 1970s. This was a model of the future of the world economy, formulated in terms of 15 regions and purporting to show the effects of resource constraints and environmental influences on the world economy.

"We had a lot of economic information about the regions, and we wanted to look at the consistency of assumptions about future trade," Carter explains. But it was the time of the Middle East oil embargo, "and we were asked mostly about energy and environment problems." As much as any one thing, that experience whetted her professional interest in electric power and widened her circle of acquaintances in that technology community.

A little more than a year ago, Carter was invited to membership on EPRI's Advisory Council. Her decision came easily from her previous experience and its lessons. Acknowledging that electricity is a pervasive energy form, she also sees EPRI as a bellwether in collaborative industrial research. And although under no illusion that technology change will ever become painless for all sectors of society, she senses the power and value of conscious leadership by the utility industry.

Carter wonders whether the Advisory Council can best help EPRI by interpreting and reporting "what's going on out there" or by recommending what electric utilities should do about it.

It is an important distinction for an industry to be decisive in dealing with change around it or to be decisive in guiding that change. This is the point of Carter's tentative vision—that EPRI and the industry it represents could be more proactive than reactive.

At their 1986 seminar, Advisory Council members and other participants were asked at one point to brainstorm upcoming issues and problems that EPRI should take into account in the course of its work. Carter believes that this matter is likely to engage the Advisory Council further. "I sense that some of us are putting ourselves in EPRI's shoes and thinking, 'The world is changing very fast, and we're in a strategic position. There's a loose ball; we can grab it and run with it.'"

Carter is quick to acknowledge that EPRI has not urged this idea upon the Council. "We're seen as ambassadors, although I think we don't especially see ourselves that way, and we're valuable for bringing in our various perspectives on the world. Now, that last is important. We're more than public relations for EPRI. The stature of the Council members, even including some curmudgeons and renegades, means that EPRI is telling the world and itself, 'We can't ignore what these people have to say.'"

But, she pointedly asks, "Do we also have a function in making the link between what we see and what EPRI does?"

Even while stumping for greater acknowledgment of advisory potential, Carter cautions that sometimes EPRI is "too respectful of professional specializations and not assertive enough about what its questions and problems are." Citing economics as an example, she says that EPRI mobilizes many of her professional colleagues, who participate in workshops and express their own views of current and future energy-economic problems.

"Imagine economizing on education in a time when we're trying to solve technical problems and the social problems that accompany them."

A wry observation suggests that Carter may be speaking from experience about how advisers and consultants select their own agendas. "The way you work, as an academic at least, is to find a question you can answer. If you find one in a hurry, you do very well."

Again in a serious vein, "I think EPRI should take the next step," she goes on, "and say something like, 'We at EPRI have thought about this, and the following questions are very important to us. We can't stop at what your profession thinks are the important questions; we want you to try to answer ours.'"

She mentions the increasing vulnerability of the world and the economically destabilizing elements that affect electric utilities. "What to do with those? A technical fix? Or do we recognize the need for social change and lobby for it? Those aren't narrow questions that an economist or sociologist can make a career on, but they're questions that EPRI has to address."

The decision to lead

Carter indulges in some blue-sky thinking about how EPRI and its members could move gradually into the technology statesmanship she is considering. "Finding projects that would involve major categories of electricity users in different regions, for example. The payoff would have to be clear," she adds. "Securing markets would be important to utilities. Strengthening membership interest would help EPRI."

Emphasizing that her thinking is far from focused or complete, Carter adds fragments of ideas that have surfaced in her conversations with other Advisory Council members: a regional experiment; governors, industrial leaders, and utility heads coming together, perhaps in a town meeting format; overall economic health as an agenda; EPRI as the facilitator, the resource "person."

The image is incomplete, but it gives some definition to the vision for EPRI that has been taking shape in Carter's mind. There is no precedent, at least not under utility industry auspices. At one moment she admits, "There'd be a selling job," and at the next moment she suggests, "You could just lead and see if they follow you!"

Carter serves on two Advisory Council subcommittees, one on alternatives for funding EPRI and another on strategic issues that seem to call for expressions of EPRI position. The creative, innovative potential of the groups and of the Council as a whole appeals to Carter, but she injects a note of modesty by saying, "It's easy for us, because we're only advisers; we don't have to take responsibility." EPRI itself is in a pivotal position, she believes. In another metaphor, she says EPRI is caught in the middle. "You have to get members to pay their dues voluntarily, and you must show them that this will help them, that they'll realize something bankable."

EPRI needs and welcomes ideas, Carter believes, but she admits that the Institute is not looking to be shaken to its roots. For one thing, the utility industry itself is notably traditional and will not be changed overnight, but given all that, she has found its individuals to be progressive and open-minded. "The discussions I've been in have been pretty freewheeling."

"Technology is such an unregulated giant. When we make choices, we have to acknowledge that whether things work out well or badly depends on much that we can't know."

The observation leads Carter to express what she has found very hopeful in her advisory experience so far. "EPRI, the industry, really, is listening to what people insist is important to them. Fifteen years ago, I remember, utilities were digging in their heels on environmental questions, claiming everyone else was irrational. Now the attitude is, 'The environment is here to stay; let's deal with it.'"

But Carter also cautions that the widely scattered and powerful impacts of technology change still haunt her. "Technology is such an unregulated giant. When we make choices (and we must), we have to acknowledge that whether things work out well or badly depends on much that we can't know." What somebody else is doing, perhaps halfway around the world, will interact or even compete.

"This is not a question of good or bad," she insists. "It is simply the nature of the problem. But with today's technology we make very powerful choices, develop very powerful innovations, without being able to know the course they'll take or the environment in which they'll function. It's a heady experience, and it can make some trouble."

Carter recalls times past, when things moved more slowly. "There was a basic inertia that protected us, held things together so we could make adjustments." The metaphor reminds her of what she believes is most important today.

"Education," she says. "I would put resources of all kinds into education. The way we educate our children and our grown people, too, will determine how well we do. Technologically, of course. But more important, how well we handle rapid change.

"My sense is that we are skimping on the resource that will give us adaptability, that will help us make wise choices. Imagine economizing on education in a time when we're trying to solve technical problems and the social problems that accompany them." ■

This article was written by Ralph Whitaker and is based on an interview with Anne Carter.

Eliminating boiler tube failures could be worth $5 billion a year to the electric power industry. The causes and cures for the great majority of these ubiquitous failures are now known, with implications for change ranging from senior management to the maintenance crew.

Winning the Fight Against Boiler Tube Failure

Boiler tube failures (BTFs) represent the largest single cause of fossil fuel plant availability disruption in the United States—equivalent to a loss of nearly 6% capacity for these plants in 1985. With thousands of BTF-forced outages occurring each year, the total cost to utilities exceeds $5 billion annually. Although these costs have continued to mount, help is on the way.

"The encouraging news is that almost all causes of BTFs are now fully understood and that permanent, cost-effective solutions are available in most cases," reports Barry Dooley, EPRI project manager in the Coal Combustion Systems Division. "Our goals now are to get this message to U.S. industry, to conduct research so that all BTFs are understood, and to develop tools and programs that will put this information into action."

The problem of boiler tube failure arises inevitably from the complexity and stresses in the environment of the fossil fuel plant. A typical boiler in these plants may contain 300 mi (483 km) or more of steel tubing, all of which is subjected to intense heat and pressure from the enclosed water and steam. The interior of tubes is chemically attacked by impurities in the water, while their exterior is corroded by combustion gases and eroded by particulate bombardment. In addition, tubes are vulnerable to fatigue from both the vibration of the operating boiler and cyclic changes in temperature.

Research has shown, however, that a large number of BTFs in the United States are repeat events that could be prevented through improvements in boiler operations and maintenance. Utilities in Canada, Great Britain, and Japan have already successfully reduced repeat failures through systematic programs to identify and address the root causes of BTF. More recently, programs of this kind have become the focus of an industry-wide effort in the United States.

As a part of this effort, EPRI has issued the *Manual for Investigation and Correction of Boiler Tube Failures,* a resource that is rapidly becoming a standard for the U.S. utility industry. Designed as a guide to BTFs, their causes, and methods for permanent repairs, the manual applies a consistent terminology to the flood of confusing and sometimes conflicting information that was previously available. The manual also provides broad guidelines for systematically investigating and correcting BTFs in the shortest possible time. To help utilities translate this information into effective action, EPRI is also establishing a two-year demonstration program on BTF mitigation, which will test the manual's effectiveness and develop training materials to go with it.

"In the manual we have tried to organize current information in a way that will be most useful to the people who actually work with boilers or manage their operation," Dooley explains. "The next step is to demonstrate the value of the manual in full use at several utilities. This should confirm that different utilities can apply the manual to minimize BTFs and improve availability of fossil fuel plants throughout the industry."

Fast but accurate investigations

The greatest concern during a forced outage—whether caused by a BTF or other problems—is to return units to service in the shortest reasonable time. Replacement power for a large fossil fuel unit can cost utilities upward of $200,000/d.

With downtime so expensive, many utilities have been reluctant to extend forced outages to the durations needed to investigate BTFs in depth. As a result, short-term repairs are made and root causes go undetected, leaving units vulnerable to repeat failures.

These time pressures were explicitly addressed in designing EPRI's BTF manual. The manual recommends a streamlined program in which failure descriptions, operating conditions at the time of the failure, historical records, and tube samples are quickly gathered and documented before repairs begin. With a small time investment, enough information is gathered to use the outage as an opportunity for learning. After the unit is back on line, the utility can continue the investigation with laboratory analyses and data reduction.

The manual guides investigation by grouping all BTFs into 22 failure mechanisms, each with distinguishing characteristics. This descriptive information is organized to help maintenance crews quickly narrow down the possible mechanisms involved in a failure; key observations and measurements of symptoms in the boiler are used to logically eliminate certain possibilities and lead investigators closer to a positive identification.

Though BTFs occur in all areas of the boiler—in water walls, superheaters, reheaters, economizers, and cyclone burner tubes—the location of a failure is the first clue to the mechanism involved. Next, visible observations of tube damage are necessary to identify the failure. Stress rupture failures, for example, are caused by excessive pressure and heat within the tubes; they often begin with the stretching, or creep, of steel and result in tube walls split open with large, fish-mouth gashes. Caustic corrosion, by contrast, is characterized by a different kind of damage: small holes gouged through the inner tube walls by caustic chemicals in the water supply.

In many cases the visible features of a BTF will not point decisively to a particular mechanism. Data on temperatures, pressures, and other operating conditions at the time of the failure must be analyzed to verify the failure mechanism. Because different stresses result in distinctive microscopic changes in steel, a metallurgical analysis of a tube sample is usually used for final verification. The manual does not eliminate the need for these analyses; instead, it provides power plant personnel with a basic terminology for describing both microscopic and easily observable damage to the tube steel. This can improve communication between boiler operators and metallurgists, making it easier for boiler operators to order laboratory work and discuss and analyze failure reports.

A further aspect of BTF investigation is the examination of adjacent tubes. The steam escaping from a tube leak can entrain fly ash particles and project them against a neighboring tube. In other instances, a violent failure can cause tubes to whip about and strike other tubes. To prevent the secondary tube failures that may result from these processes, the manual outlines steps for rapid exam-

Research on Root Causes

Of the 22 failure mechanisms identified in EPRI's BTF manual, only two require further R&D to determine the root cause: corrosion fatigue failures that begin on the water side of waterwall and economizer tubing, and circumferential waterwall cracking that begins on the fire side of supercritical units.

The corrosion fatigue failures—the single largest cause of availability loss from BTFs—are caused by a combination of corrosive water chemistry and cyclical changes in operating temperature. They loom as especially problematic to the many utilities who are switching baseload plants to cycling or two-shift operation.

Accordingly, corrosion fatigue is the focus of a separate EPRI effort to identify the conditions of stress and water chemistry that cause this failure mode. The project involves laboratory experiments on the effects of corrodants and varying temperatures on tube materials, as well as in-plant monitoring of changing conditions in four test boilers. Another study is under way to monitor test boilers and delineate the conditions causing supercritical waterwall cracking.

EPRI is also supporting research into corrosion and fly ash erosion on the fire side of tubes. The root causes of these common failure mechanisms are well understood, but more work is needed to explore the effectiveness and economics of permanent solutions. A planned EPRI project will investigate two permanent solutions that have been implemented and documented in Great Britain and Canada. These measures include the use of stronger alloys and cladding in tube design and a method for monitoring the velocity and movement of cold air through the boiler. This latter technique establishes a matrix for the location of diffusing screens, baffles, and shields that can permanently protect the fire-side tube walls from erosion and corrosion. Current research is aimed at giving U.S. utilities a firm basis for comparing the costs and results of these permanent solutions with the alternative of continued maintenance and (in some cases) repeat failures.

Research on coal quality will also play a part in minimizing BTFs and improving availability. Erosive properties of fly ash vary with different coals, as do the slagging and fouling processes that sometimes cause tube blockages, overheating, and tube failures. EPRI is currently sponsoring a comprehensive effort to develop a coal quality impact model (CQIM) that will account for the effects of changes in coal quality on boiler tubes and all other relevant plant equipment. CQIM will also be used to balance likely maintenance and availability costs against prices of different coals, which will allow utilities to calculate the net differential cost of electricity generation. □

ination of damage to tubes adjacent to a BTF. Before repairs are made, ultrasonic measurement techniques (described in a separate appendix to the manual) may be useful for determining the remaining wall thickness of tubes that have been eroded or otherwise damaged. In other cases, the examination of a tube that has been damaged on the outside from erosion or corrosion may lead investigators to steam leaking from a failure in another tube.

Correcting root causes

Identification of the failure, though crucial to its correction, is most valuable as a path to the operating conditions or root causes that generate the failure mechanism. In some cases, BTFs originate with simple human errors—tubes can be poorly fabricated or installed in the wrong section of the boiler. More often, however, failures begin with such factors as blockages and undetected leaks in other tubes, poor quality control in maintenance and repairs, poor water chemistry, and operating practices, such as cycling and two-shifting, that subject tubes to unusual thermal stresses.

Root causes are understood for 20 of the 22 failure mechanisms described in the EPRI manual, and permanent solutions have been developed for 18 of them. Many of these permanent solutions involve new or more carefully controlled techniques for boiler maintenance. For example, effective chemical cleaning is needed to remove and prevent the deposits that sometimes cause tubes to overheat and fail. Faulty welds can also leave tubes overly vulnerable to stress, as can maintenance practices that overlook the gradual thinning and deformation of tubes.

Ultrasonic testing (UT) and other nondestructive evaluation (NDE) techniques are useful during many forced outages (as well as during scheduled maintenance) to detect such failures waiting to happen. EPRI has developed computer codes to help utilities analyze UT inspection data and determine maintenance

The Many Facets of Failure

Researchers have identified 20 root causes of the 22 mechanical processes that cause boiler tubes to fail, and permanent, cost-effective solutions are available for 18 of these failure mechanisms. Work is now in progress to provide the industry with the understanding and techniques needed for root cause prevention and correction of all boiler tube failures.

PRIMARY MECHANISMS

Stress Rupture
- Short-term overheating
- High-temperature creep
- Dissimilar metal welds

Water-side Corrosion
- Caustic corrosion
- Hydrogen damage
- Pitting (localized corrosion)
- Stress corrosion cracking

Fire-side Corrosion
- Low temperature
- Waterwall
- Coal ash[1]
- Oil ash

Erosion
- Fly ash[1]
- Falling slag
- Sootblower
- Coal particle

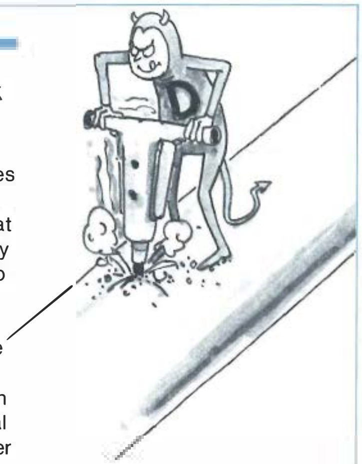
Fatigue
- Vibration
- Thermal[2]
- Corrosion[2]

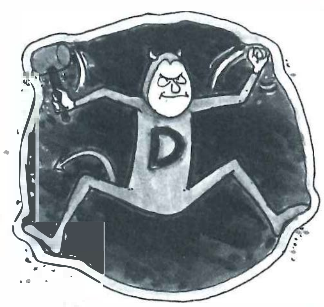
Lack of Quality Control
- Maintenance cleaning damage
- Chemical excursion damage
- Material defects
- Welding defects

1 Root cause known; permanent solutions in development.
2 Root cause not known.

Boiler Tubes Under Attack

In the complex environment of a fossil fuel boiler, tubes are subjected to multiple stresses that can work individually or in combination to cause failures. Combustion gases bombard outer tube walls with erosive particulates and can also cause chemical corrosion; poor water chemistry can corrode tubes with an alkaline or acid attack on inner walls; fatigue failures can result from vibration and thermal stresses often related to cyclic operation of the boiler; and intense heat and pressure can combine to stretch tubes, eventually causing them to rupture.





An Example of the Manual in Use: Caustic Corrosion

EPRI's *Manual for the Investigation and Correction of Boiler Tube Failures* guides utility personnel through a logical system of examination and analysis to narrow down the mechanism and root cause of a tube failure. Below, in a shortened form, are the manual's basic procedures and information for identifying and treating one common failure mechanism, caustic corrosion.

1. Locate the failure. Caustic corrosion failures occur in water-cooled tubes in boiler superheaters and waterwalls. Many of these tubes have flow disruption, such as from welded joints with backing rings or protrusions, bends, or deposits. Other tubes are either horizontal or inclined, or are subjected to intense heat or extreme temperature changes.

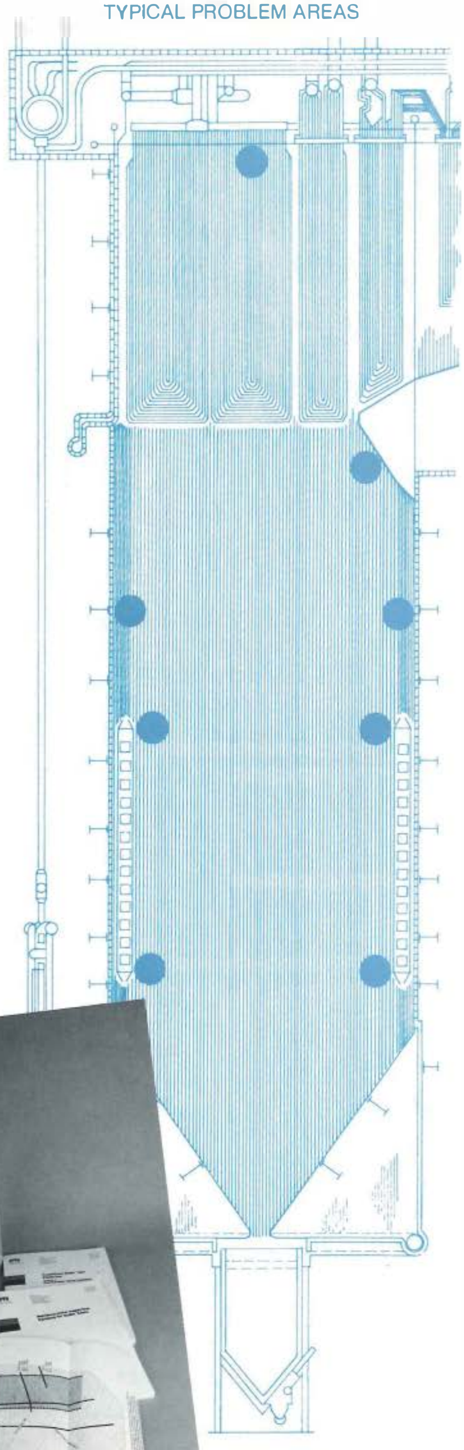
2. Examine the visible damage. Thin-edged ruptures or pinhole leaks are found in inner tube walls. A thick deposit of corrosion products is usually present on the internal surface.

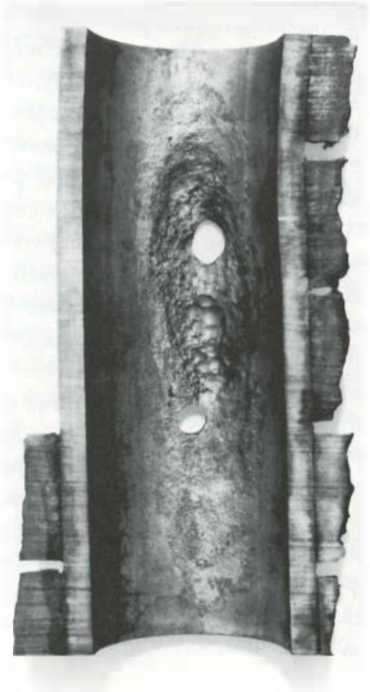
3. Verify the root cause. Caustic corrosion is caused by upsets in boiler water chemistry and deposits of sodium hydroxide on inner tube walls. For verification, monitor condenser leakage from freshwater cooling bodies. Collect tube samples to analyze deposits. Verify upsets and errors in water chemistry by reviewing chemical control logs, on-line water chemistry records, and instrumentation alarms.

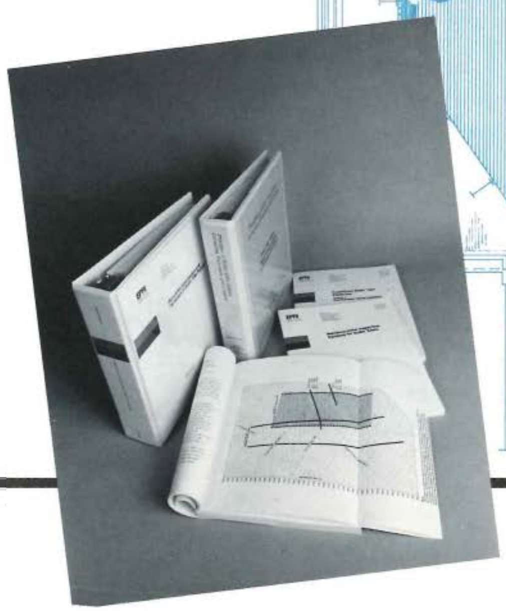
4. Take corrective action. Control chemistry in feedwater and condenser leakage to minimize entry of corrosion products. Remove corrosion deposits with chemical cleaning. Where possible, eliminate vulnerable welds and surface irregularities. Use less-susceptible materials in replacement tubes.

5. Check for incipient damage. Use ultrasonic and radiographic techniques to check for wall thinning in vulnerable tubes. Monitor tube metal temperatures with thermocouples to indicate deposits of corrosion products.

TYPICAL PROBLEM AREAS







intervals, and it has issued procedural guidelines for the efficient and cost-effective use of the technology. In addition, evaluations are in progress for advanced NDE techniques that may enhance or replace UT. Electromagnetic acoustic transducers (EMATs) send electromagnetic waves directly through the layer of corrosion on a damaged tube to interact directly with the tube wall. This eliminates the time-consuming need to first grind away the corrosion layer before ultrasonic inspection. A related technique, infrared thermography, shows promise for scanning large areas of the boiler to find pitting, tube blockages, and wall wastage that indicate a high likelihood of future tube failures.

Utilities are also improving their understanding and control of boiler water quality, a major root cause of tube failures. Boiler water must be closely monitored for pH; tubes can be damaged from the inside by either alkaline or acid attack, as well as by dissolved oxygen and a range of contaminants. Increasingly, utilities are establishing plant- and organizationwide programs to protect their boilers through careful treatment and monitoring of the water supply. To aid such efforts, in 1986 EPRI issued water chemistry guidelines as part of a project on overall fossil plant cycle chemistry. These consensus guidelines are applicable to baseload, cycling, and peaking operations in the majority of utility fossil fuel boilers.

A commitment to investigation

Cataloging these and other solutions is a large step toward reducing BTFs and improving availability across the industry. However, the real success of these efforts, first and foremost, depends on the willingness of individual utilities to take action. Currently, such commitment is being demonstrated in a hands-on program being sponsored by EPRI and 10 host utilities. The utility participants, representing nearly 100,000 MW of fossil-fuel-fired capacity, will use the information and recommendations in the BTF manual to rigorously report and investigate all their tube failures over the two-year demonstration.

In addition to testing the accuracy and value of the manual, the project includes the development of training materials for utility personnel at many different levels of responsibility—from maintenance people doing tube repairs to top executives who must commit time and resources.

"The training materials being used in the demonstration support the manual's classification of failure mechanisms and basic procedures for investigation and correction of BTFs," explains John Dimmer, an engineering specialist who is helping EPRI to develop the materials. "Going beyond the manual, however, the new materials offer a detailed, programmed approach for identifying, verifying, and correcting BTFs. We are gradually developing a comprehensive training program that will unify the efforts of everyone involved with investigating BTFs at each utility."

An important goal of this systematic approach is to provide people at different levels of an organization with a shared philosophy and a common language for dealing with BTFs. "Using this program, project leaders can call a foreman at any one of our fossil fuel plants and quickly get an understanding of the mechanism involved in a tube failure," adds Bernard Herre, senior project engineer at Pennsylvania Power & Light Co. and the utility's project leader for the demonstration. "Because all BTFs are being reported in a uniform way, we can look at failure trends and make decisions about the timing and the implementation of the solutions available."

While improving the communication within utilities, the demonstration will also lay the groundwork for improved communication on BTFs across the entire industry. During the demonstration project, the participating utilities will establish a new root cause data base that may serve as the model for a future nationwide system. Currently, EPRI and the North American Electric Reliability Council (NERC) are discussing the possibility of including data on BTF mechanisms and root causes in NERC's generation availability data system (GADS). With regard to BTFs, GADS is currently limited to data on the location of events within the boiler.

"The failure mechanisms and root causes in the EPRI manual can easily be incorporated into our systems," states Ronald Niebo, director of GADS. "We'll be monitoring the demonstration to see if this kind of reporting turns out to be practical and valuable for the participants."

In the last analysis, the effect of these and other attempts to understand BTFs will be directly related to the industry's commitment to report, investigate, and wherever possible, correct the conditions that cause boiler tubes to fail. "As we hope to demonstrate, current knowledge in this field has the most value when it is systematically and rigorously applied," comments Dooley. "With fossil fuel boilers figuring ever more prominently in the generation needs of the industry, I think we have an excellent opportunity to achieve some impressive improvements in reliability." ■

Further reading

State of the Art of Maintenance and Repair Technology for Fossil Fuel Boilers and Related Auxiliaries. Final report for RP2504-1, prepared by General Physics Corp. and Duke Power Co. In press. EPRI CS-4748.

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This article was written by Jon Cohen, science writer. Background information was provided by Barry Dooley, Coal Combustion Systems Division.

TECH TRANSFER NEWS

Fast Access to Life-Test Data on Safety Components

Of the 25,000 equipment items in a nuclear power plant, 25–30% are in various safety systems. NRC regulations require that the life of each safety-related component be verified (qualified) by the utility. Although suppliers provide basic product information to utilities and in most cases perform qualification tests, the utility bears the responsibility for the qualification of that equipment. It is a formidable task, requiring artificial aging and radiation conditioning of each item to the end of its design lifetime and then successful operational testing during seismic simulation and under postulated accident conditions of temperature, pressure, and chemical spray. Qualification of one piece of equipment can take months and cost hundreds of thousands of dollars.

Given such costs, there is considerable incentive to compile qualification data so that successive utilities need not repeat tests unnecessarily. EPRI therefore established the equipment qualification data bank (EQDB) in 1979 as a comprehensive index to summary test data and utility test reports.

Utility members of EPRI's Equipment Qualification Advisory Group are the major EQDB source of data. NUS Corp. collects data from reports received directly from utilities and from those in the NRC public document room; it also adds EPRI research data to keep EQDB current. Access is by subscription, with an annual fee of $9000 for EPRI members and higher fees for nonmembers.

A utility using EQDB still must qualify its equipment for its particular environment and function, but test reports of other utilities often provide data for the same or similar equipment in different environments, thus expediting the qualification in areas of data similarity.

EQDB provides peak values from test data and references that can be used to pursue more-detailed analyses—test reports, contact names, and telephone numbers. The contents of the data bank are organized into three main categories: environmental and seismic data, material properties, and manufacturers' catalog of safety-grade equipment. The first category includes electrical and mechanical equipment, and the second includes radiation and thermal effects on organic components, such as O rings, insulators, and lubricants.

Brett Ayotte of NUS Corp., the administrator of EQDB, regards the manufacturers' catalog (the third and newest portion of the data base) as having enormous potential. George Wrobel, a senior licensing engineer at Rochester Gas and Electric Corp., looks forward to using the catalog to find all the sources for parts to be used in plant modifications.

Edward Gouvier, a senior equipment qualification engineer for Arizona Nuclear Power Project's Palo Verde plant, sees EQDB as "an excellent starting point for information to establish or revise qualification, especially when working to a tight schedule." ANPP has supported EQDB since it was established, using it in conjunction with an ANPP plant-specific data base with more than 1000 (model-number-based) qualification summaries.

For example, referring to EQDB for information on activation energies and radiation thresholds, ANPP has reviewed manufacturers' suggested replacement intervals for many items. ANPP then scans the replacement items in its own data base, beginning with those that have the shortest qualified life. Using experience and judgment, ANPP reviews the underlying calculations in cases where replacement intervals may be unduly conservative. Finally, with data on the actual operating environment for the equipment and EQDB information on the properties of its materials, ANPP decides which candidate items deserve in-depth qualification reanalysis.

ANPP has had remarkable success with EQDB. In one instance, a supplier of valves had recommended replacement of the packing and seals at 18-month intervals. Because each of the ANPP units

contains 67 of these valves, the maintenance and documentation burden for this one item would have been enormous. Using such factors as the valves' infrequent use and data on the materials from EQDB, ANPP successfully established a 20-year life, replacing valve packing and seals only once during the lifetime of the plant, instead of 27 times.

A second example involved O rings and seals that were qualified by a supplier for 2½ years. Review of the calculations prompted an in-depth analysis and subsequent justification of a 13-year replacement interval. In a third, EQDB gave ANPP a head start toward qualification information that was needed on a crash basis. The problem involved a nonsafety-related sampling system required to remain operable after an accident. During design verification review, ANPP discovered the system itself was subject to substantial doses of radiation from the process fluids and gas that it sampled. As the ANPP qualification data base did not cover all the materials used in the sampling system, it turned to EQDB and obtained the needed radiation effects information from the materials library therein. In Gouvier's words, "EQDB is an excellent card catalog for qualification information, and ANPP expects to support it in the future."

Contacts: Brett Ayotte, NUS Corp.; Edward Gouvier and Martin Raines, Arizona Nuclear Power Project; George Wrobel, Rochester Gas and Electric Corp. ■ *EPRI Contact: George Sliter (415) 855-2081*

Dam Inspection and Performance Evaluation

Managers, engineers, and operators of hydroelectric projects can turn to a new resource, *Inspection and Performance Evaluation of Dams* (EPRI AP-4714), to maintain the safe and economical performance of dams, spillways, and other appurtenant works. Both large and small utilities can use these guidelines to establish inspection/evaluation programs that will keep their dams in compliance with government regulations and current engineering practice.

Designed to be useful both in the field and in electric utility engineering offices, the guide includes inspection checklists, inventories of potential structural and equipment problems and their effect on dam performance and life, and detailed accounts of remedial action. It also gives information on the concept and organization of inspection/evaluation programs, reporting procedures, and the development of communication channels. One chapter covers emergencies caused by either natural occurrences or project-related problems, describing federal requirements for emergency action planning and outlining a typical action plan. ■ *EPRI Contact: Charles Sullivan (415) 855-8948*

Heat Rate Improvement

Increased cycling requirements, worsening fuel quality, and stringent environmental regulations have contributed to deteriorating heat rate performance in many fossil fuel electric power plants. As a result, several utilities have experienced increases in fuel costs that amount to millions of dollars each year.

To reverse this trend, utilities can refer to the *Heat Rate Improvement Guidelines for Existing Fossil Fuel Plants* (EPRI CS-4554). These generic guidelines draw on current literature and industry experience to help utilities implement heat rate improvement programs. Guidance is offered on justifying, initiating, monitoring, and managing these programs to both optimize plant performance and fit within the resources of the individual utility. The section on program implementation offers low-cost activities for producing immediate performance improvements, as well as methods for identifying the degraded performance of critical components that affect plant heat rate. ■ *EPRI Contact: Gary Poe (415) 855-8969*

Integration of Ratemaking and Demand-Side Planning

A utility's ratemaking and demand-side management (DSM) activities can work at cross purposes. To prevent this, utilities can use a new analytic framework to calculate the best combinations of rate structures and DSM programs to meet their overall objectives.

The four-step framework is used for ascertaining and weighing a utility's ratemaking and load-shape objectives, for defining rate design–DSM combinations, for tracking the interaction between rates and DSM programs, and for quantifying the degree to which individual combinations achieve corporate objectives. Information and materials for using this analytic framework are included in a recent report, *Impact of Rate Structure on Demand-Side Management Programs, Vols. 1 and 2* (EPRI EM-4791, Vols. 1 and 2).

Besides describing the framework and documenting utility case studies in Vol. 1, the report gives worksheets and summary tables for utilities to use in clarifying rate design and load-shape objectives in Vol. 2. The worksheets are versatile: they can be used with Lotus 1-2-3 software on IBM-compatible microcomputers, modified for use with other spreadsheet software, or serve as guides for manual calculations. ■ *EPRI Contact: William M. Smith (415) 855-2415*

Cogeneration Handbooks

Using cogeneration in mixed-use and industrial parks can reduce energy costs and smooth out peak load demands—potential benefits for both utilities and their customers. A new series of handbooks, *Cogeneration for Industrial and Mixed-Use Parks, Vols. 1–3* (EPRI EM-4576) can help both groups evaluate the suitability and the benefits of cogeneration at planned or existing parks.

The first handbook (Vols. 1 and 2) outlines a step-by-step method that utilities can use to evaluate mixed-use and industrial parks as cogeneration sites. The method uses screening criteria that include the presence or potential of significant thermal loads, the ability to obtain environmental permits and approvals, the potential for utility co-ownership, and the interest expressed by park tenants or owners. The second handbook (Vol. 3) describes the benefits of cogeneration for park developers, owners, and tenants. ■ *EPRI Contact: S. David Hu (415) 855-2420*

R&D Status Report
ADVANCED POWER SYSTEMS DIVISION

Dwain Spencer, Vice President

CAPACITY PLANNING WITH PHASED–GCC ADDITION

Utilities are becoming increasingly involved in evaluating the phased addition of gasification–combined-cycle (GCC) capacity. Two utilities, Potomac Electric Power Co. and Virginia Power, have publicly announced their individual intentions to pursue a phased-GCC implementation plan. The reason for this utility interest lies in the usefulness of phased GCC in addressing capacity planning in its many dimensions. For instance, when measured against alternative capacity options, phased-GCC addition compares favorably in terms of factors that range from ratepayer impact to utility risk to shareholder interests.

EPRI has sponsored several studies of phased-GCC capacity addition. A planning data book has been created to provide utility planning engineers with the information that they require to conduct an analysis of phased-GCC implementation on their systems (AP-4395). Many of the 12 utilities that participated in directing the development of this data book have since conducted their own evaluations of phased-GCC construction.

In addition, EPRI contracted with Zaininger Engineering Co. to perform generic system expansions by using the phased-GCC scenarios from the data book (RP2699-4). These generic system studies focused on one dimension of a utility planning analysis, that of the present worth of revenue requirements (PWRR). Because this PWRR parameter translates into the ratepayer impact that will be associated with any given planning scenario, it is a critical factor.

Several scenarios were examined in EPRI's generic system planning studies. In each scenario, a hypothetical 4000-MW coal-based utility served as the backdrop for the comparison. The results of production costing analysis of four scenarios are summarized in Table 1. The first scenario (unphased GCC) consists of a 362-MW GCC plant installed as one block of capacity in the year 1993. The second scenario (phased GCC) provides for the sequential addition of combustion turbines, one in 1993 and another in 1994. The gasification facility, which converts this capacity to a 362-MW GCC, is subsequently installed in 1995. The third scenario (phased GCC, delayed gasification) is identical to the phased-GCC plan with the exception that installation of the gasification facility is delayed until 1998. In the fourth scenario (combined cycle), the unphased installation of a 362-MW combined-cycle facility is completed in 1993.

As shown in Table 1, the PWRR consistently decreases in going from the unphased-GCC plan to the combined-cycle expansion. This indicates that over the 10-yr study period (1993 through 2002), the delay or reduction of capital expenditures yields a PWRR saving that is not substantially offset by rising fuel costs. In other words, it is preferable to delay until 1998 the addition of the gasification plant when compared with the 1995 installation of the phased-GCC expansion plan. Likewise, it is even more attractive to defer the gasification plant addition beyond the 10-yr study period, as evidenced by the low total PWRR for the combined-cycle expansion plan, assuming that the actual future oil prices are consistent with the projections used in this study.

As suggested above, this conclusion is based on certain assumptions about fuel prices. The assumed mid 1986 distillate oil price was $\$6/10^6$ Btu, and it was escalated at 7.5%/yr. The assumed coal price was $\$1.70/10^6$ Btu, and it was escalated at 6.9%/year. Given these fuel price assumptions, it can be predicted that at some time after the 10-yr horizon of the EPRI analysis, the higher oil prices will catch up with the combined-cycle expansion plan, making the eventual conversion to a GCC facility the most economic alternative.

However, there is a great deal of uncertainty in these fuel price projections; for that matter, uncertainty surrounds almost every assumption in the planning process from load growth projections to estimates for the future cost of capital. These uncertainties lead us to a second dimension in the capacity planning process: the need to reduce economic risk by

Table 1
PRESENT VALUE OF REVENUE REQUIREMENTS FOR EXPANSION PLANS
(mid 1986 $ million)[1]

	Unphased GCC	Phased GCC	Phased GCC Delayed Gasification	Combined Cycle
Production Costs				
Oil	$ 27	$ 53	$ 72	$ 188
Coal	1862	1860	1859	1829
O&M[2]	432	417	404	388
Subtotal	2321	2330	2335	2405
Fixed charges[3]	512	424	337	145
Total (PWRR)	$2833	$2754	$2672	$2550

[1]For period 1993 through 2002.
[2]Includes variable O&M for all units and fixed O&M only for new capacity.
[3]For capacity unique to each scenario.

maximizing flexibility. Once again, phased-GCC construction compares favorably with alternative generation options because it allows for controlling the rate at which phases are added in response to changes in either fuel prices or electric load growth.

There are many other factors by which utilities measure and compare new generation alternatives independent of the PWRR standard and the flexibility objective. They include the capital tied up as construction work in progress (CWIP); the allowance for funds during construction (AFDC); shareholder return; high bond ratings; construction lead time; efficiency; regulatory risk; environmental risk; and technology uncertainty.

When utilities evaluate these factors (either quantitatively or subjectively), phased-GCC addition fares quite favorably in comparison with other new generation alternatives. The exception to this rule lies in the area of technology uncertainty where limited experience with gasification in the electric utility application imposes a certain degree of technical and financial risk for the utilities that pioneer the application of this technology. *Project Manager: Allison Lewis*

ACOUSTIC HYDRO FLOW MEASUREMENT SYSTEMS

In 1981 EPRI initiated a research project to demonstrate the technical and economic characteristics of an acoustic flow measurement system (RP2038). Researchers hoped that the project results would provide the basis for the system's inclusion into various test codes and would allow hydropower producers to optimize output, diagnose major equipment problems, and ensure turbine warranty specifications. Three power producers—British Columbia Hydro (BCH), U.S. Bureau of Reclamation (USBR), and Tennessee Valley Authority (TVA)—provided units representing a wide range of field conditions for tests at their respective sites: Kootenay Canal power station, Grand Coulee pump/generating station, and Raccoon Mountain pump-storage plant. To date, all testing has been completed, and the data have been presented to the American Society of Mechanical Engineers (ASME) and International Electrotechnical Commission (IEC) code committees.

Many hydropower producers are currently considering modernizing their plants. A principal candidate approach is to monitor continuously the water flow rate through the turbines. Without periodic measurements of flow, hydro plant operators can have little confidence in their unit's efficiency curve, how far from optimal efficiency a unit is, or how a unit's performance compares with its original specifications. An acoustic flow measurement system (AFMS) will provide all this information continuously, assess major equipment problems, and record discharged water to ensure that minimal stream flow requirements are being met. When accepted for test codes, an AFMS could be used to establish actual performance versus the warranty specifications for both new (original) and replacement turbines.

Most of the accepted methods for measuring flow rate are expensive, require a great deal of manpower, result in power loss during testing, and are one-time (not continuous) measurements. No continuous method of determining a hydro plant's efficiency has been formally accepted to date. For many penstock applications, however, one of the most recent options available is the acoustic flow measurement technique. It costs approximately the same as one test series of an accepted method, yet it measures flow continuously with no loss of power. This measurement method works on the principle that it takes longer for an acoustic (ultrasonic) signal to propagate against the direction of water flow than with it. This difference in travel time between measuring stations is converted into water velocity and then integrated to give flow rate; an accuracy of 0.5% is achievable in many field applications. This method has not been widely accepted partly because it is fairly new, and the national and international turbine and pump test code committees have yet to evaluate it.

Kootenay Canal

The first test was carried out during October and November 1983 at Kootenay Canal power station in British Columbia. The site has an intake structure, four penstocks 780 by 22 ft diam (256×7 m), and four 132-MW Francis-type turbines. The site has a 245-ft (80-m) head, with each penstock designed to carry water in excess of 6000 ft^3/s (170 m^3/s).

Seven organizations participated in the tests of seven flow measurement methods, not all of which are accepted by both ASME and IEC. EPRI chose the late Lawrence Neale of Charles T. Main, Inc., as test director to organize, coordinate, and certify that the testing was performed in accordance with current standards. The two major suppliers of acoustic systems—the Accusonic Division of Ferranti Ocean Research Equipment, Inc. (ORE), and Westinghouse Electric Corp.—were both represented.

A primary objective was to compare the acoustic method with other methods. A secondary objective was to investigate the dye-dilution method because it may have some unique applications and advantages. For this measurement, dye is injected upstream at a precise rate; the mixed concentration is measured downstream; and the flow rate is calculated. This method can be cost-effective for power producers that have trained teams to carry out such tests routinely at small-hydro sites.

All flow measurement instruments, except those for the dilution technique, were located entirely in the upper penstock area. Investigators tested seven flow measurement methods, representing five techniques.

- Acoustic flow measurement. One method used the Westinghouse leading-edge flowmeter (LEF) supplied and recorded by BCH personnel; a Westinghouse representative was present at all times. A second method used the ORE flowmeter supplied, installed, and recorded by Accusonic.

- Pressure-time. Stanley Consultants, Inc., used the code-accepted Gibson method with a differential mercury manometer recording onto photographic film. The Essais de Réseau et Analyse–Hydro-Québec method incorporates the same pressure-time principle as the Gibson method, with pressure measured by a transducer and flow calculated numerically with a minicomputer; this method is not currently code-accepted.

- Currentmeter. The Hydro-Québec method had 52 currentmeters mounted on a frame inside the penstock; this method is code-accepted. The currentmeter was one of two methods used to determine reference discharge.

- Dye-dilution. Both Ontario Hydro and Pacific Gas and Electric Co. (PG&E) used this method, which is IEC code-accepted.

- Allen salt-velocity. This method, used by USBR, measures the average travel time of a salt cloud over a known distance between two electrodes inside the penstock; it is code-accepted and was the second method used to determine the reference discharge.

The Accusonic ORE system had two-crossing, four-path planes, each at an angle of 45° to the penstock axis, whereas the Westinghouse LEF system had the same arrangement at an angle of 65° to the axis. The Stanley-Gibson method consisted of pressure taps 80 ft (24 m) apart that measured transient pressure while the wicket gates were rapidly closed. The Hydro-Québec version of this measurement technique was more automated and less subjective, but it still required that the plant be out of service during testing.

Hydro-Québec's currentmeter method is widely accepted but requires expensive pre- and posttest calibration, draining of the plant, and installation of a substantial structure to support the 52 currentmeters inside the penstock. It is very difficult to find a facility for calibrating such meters in North America, especially for high velocities. If problems arise during testing (as they did in this case), the penstock must be drained to the currentmeter level and repairs made. Such a currentmeter test series would cost at least $50,000, not including the cost of currentmeters or replacement power. Dye-dilution testing also requires draining and lost power; such a test series costs approximately $35,000. The environmental effects of the type of dye used can also be a concern.

The Allen salt-velocity method required the most massive support (several tons) inside the penstock. An upstream structure held salt solution injectors, and two downstream structures, separated from each other by 200 ft (66 m), held the electrodes. Custom fabrication and installation to make this equipment compatible with the penstock required a lot of time. This method was probably the most expensive and time-consuming.

Preparation required one month, and testing required seven consecutive 12-h days to complete. The AFMS data agreed with the widely accepted currentmeter, salt-velocity, and Hydro-Québec pressure-time data (Figure 1). The Gibson (Stanley Consultants) and dye-dilution data compared less favorably.

BCH recognized the economic and accuracy advantages of AFMS some time ago and had a single-plane system installed for $18,000. A second plane was installed as part of this research for the same cost in 1983.

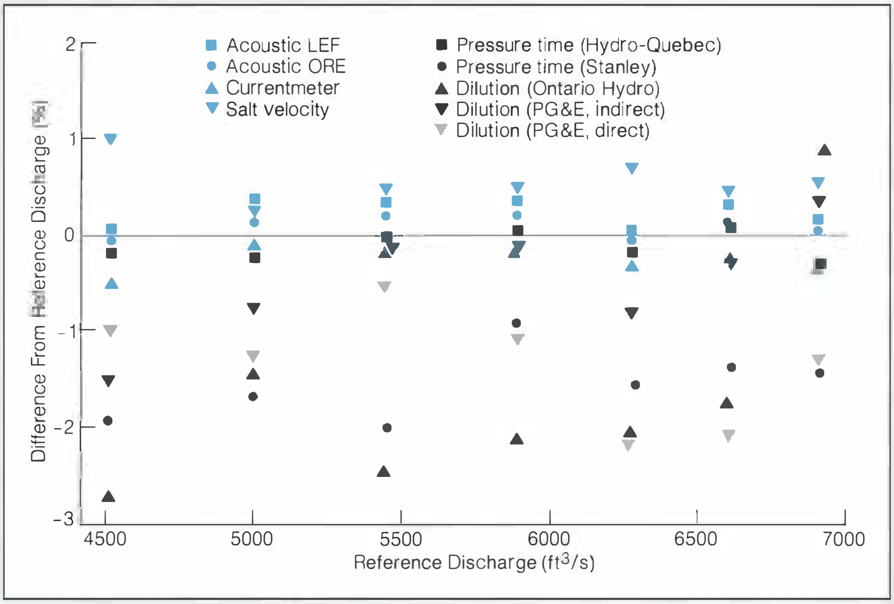
Grand Coulee

Researchers carried out a second series of tests in March 1984 at the Grand Coulee project in Washington. The unit tested was Pump/Generator No. 9, which can either pump water uphill from Roosevelt Lake to Banks Lake for irrigation or generate electricity by sending water in the opposite direction. The pump/turbine is rated at 54 MW, has a 280-ft (92-m) head, and is connected to a 916-ft by 12-ft-diam (300 × 4-m) penstock that carries approximately 2000 ft^3/s (706 m^3/s) of water.

Six organizations participated in this test series. USBR used the Allen salt-velocity method and a volumetric method; Stanley Consultants, the Gibson (pressure-time) method; Hydro-Québec, the transducer pressure-time method; Ontario Hydro, the dye-dilution method; both Westinghouse and Accusonic ORE, the acoustic method. The AFMS participants were located near an elbow in the penstock so that each would be downstream of a flow disturbance in one flow direction or the other.

The physical features of this site made the addition of the volumetric measurement method possible. During pumping, the penstock discharged into a canal that carried the

Figure 1 Comparison of flow measurement methods at Kootenay Canal. The currentmeter and salt-velocity methods established the reference discharge, which equals the average of all salt-velocity and current meter runs. (The PG&E direct method is an immediate measurement; the indirect method is measurement after resting for a minimum of 2 h.)



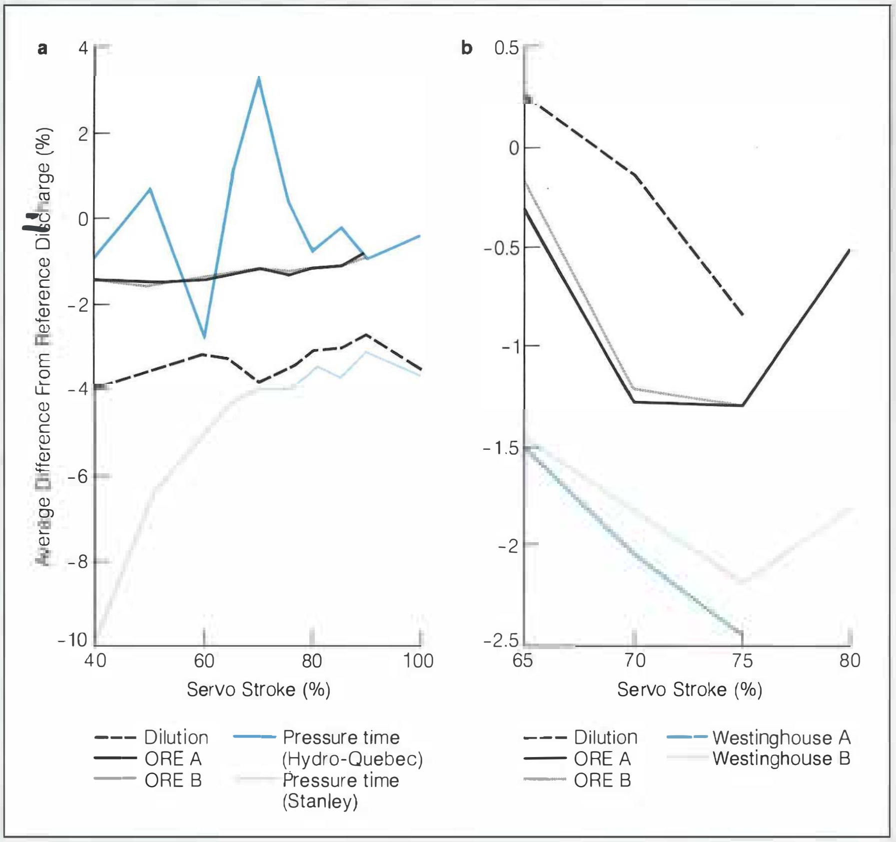


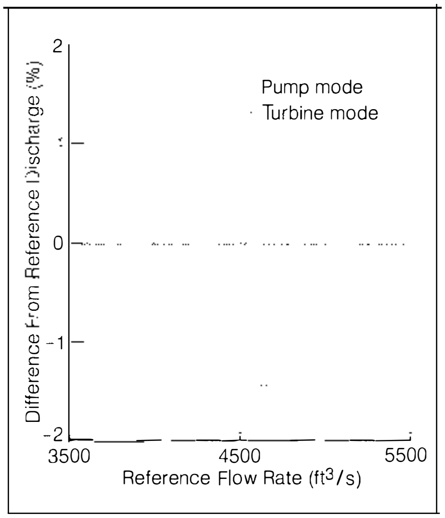
Figure 2 Comparison of flow measurement methods at Grand Coulee for (**a**) the turbine mode and (**b**) the pump mode. The percent difference from the reference discharge is based on an average of points. The reference is an average of salt velocity points.

water into Banks Lake. This canal was isolated from the lake and drained so that the water level could be measured as water was pumped in during a test. Tests were long enough to permit this measurement. The code-accepted methods were arranged in a manner physically similar to that used at Kootenay Canal except that a turbulator (set of steel cross members) was installed just downstream of the salt solution injection point to improve mixing.

The flow comparison test was conducted in two phases; first the unit was operated in the pumping mode. Flow was measured by acoustic flowmeters, dye dilution, and salt velocity, and the results were compared. The second test phase was carried out while the unit was operating as a turbine. In this mode, comparative flow measurements were taken by the ORE acoustic flowmeter, dye-dilution, salt-velocity, and both pressure-time methods. Entrained air, created by vortices at the penstock entrance, prevented Westinghouse from obtaining reliable data; as a result, that company did not submit data for the turbine test phase.

Figure 2(a) shows typical data from the turbine test phase. The bandwidth of these measurements is greater than the data from the pumping mode. The pumping mode did have the advantage of better mixing of the injected dye and the absence of entrained air. Figure 2(b) shows examples of data taken during pumping; the reference discharge is an average of Allen salt-velocity points. Measurement accuracy is misleading because the absolute flow rate is unknown. The canal volumetric tests were hampered by waves from pump startup and wind, but in the project conception, researchers recognized that this phenomenon would be a risk. The integrated ORE measurement was to within 1% of the before-versus-after canal volume. The Westinghouse system was not set up to sum the flow over time.

Figure 3 Measurement of pump and turbine discharge at Raccoon Mountain. The reference is based on volumetric calculations.



Raccoon Mountain

This third test site was TVA's Raccoon Mountain pumped-storage plant located near Chattanooga, Tennessee. Four 385-MW reversible pump turbines operate between Nickajack Reservoir and another reservoir about 1000 ft (328 m) above. The maximum flow was about 5600 ft^3/s (159 m^3/s) during generating and about 4500 ft^3/s (127 m^3/s) during pumping.

Volumetric calibration of the upper reservoir and testing was completed in September 1984 with TVA's existing Accusonic ORE four-path system located in a section of the penstock that was 10 ft (3 m) in diameter. The acoustic measurements were compared volumetrically with elevation readings in the upper reservoir. Other methods were not incorporated because of interference with plant operations.

The Raccoon Mountain site offered the highest head of all three sites, along with a large penstock and high flow rates. The location of this AFMS—near a change in a cross-sectional area—challenged the system's ability to accurately measure the flow in a nonuniform flow field. Figure 3 compares the volumetric and acoustic flow measurement data. The acoustic technique gave results with a mean value of 1.5% less than those from the volumetric method. Potential causes for this difference could be a survey error in the acoustic alignment or flow pattern irregularity not captured by the four-path array.

In spite of the challenges presented by the site, the acoustic data agreed very well with the volumetric results. The fact that the acoustic method always produced lower results than the volumetric measurements indicates some systematic error may exist in one or both measurements.

Test results

The extensive data on the AFMS from all three test sites have exceeded researchers' expectations. All three test reports have been presented to the ASME and IEC code committees as documentation, and changes to the test codes have been recommended on the basis of this work. EPRI is currently sponsoring additional comparison tests with Southern California Edison Co., using the IEC code-accepted thermodynamic test method. The flows determined for a Francis-type turbine will be compared with those measured by an existing acoustic flowmeter. This comparison is expected to further validate the accuracy of the acoustic method.

Considering the documented accuracy and competitive cost, more power producers are expected to install such systems on the basis of these test results. In fact, because the economic benefits are so substantial, hydropower producers should seriously consider such systems even before the code committees accept them. *Program Manager: Charles W. Sullivan*

R&D Status Report
COAL COMBUSTION SYSTEMS DIVISION

Kurt Yeager, Vice President

NONDESTRUCTIVE EVALUATION OF TURBINES AND AUXILIARIES

Nondestructive testing to assess the condition of critical power plant components is the key to maintaining high levels of availability and performance, particularly in older fossil fuel units. The ability of nondestructive testing to detect and size material flaws and to characterize material properties provides the basis for estimating remaining component life. Such equipment tests and subsequent analyses make up the technology known as nondestructive evaluation (NDE). This report describes emerging inspection techniques for turbine components and heat exchangers.

Visual, liquid penetrant, and magnetic particle testing are common NDE methods for detecting surface-connected flaws. These methods are highly operator-dependent, however, and their sensitivity can be affected by extremely tight cracking, complex geometries, corrosion products trapped in discontinuities, and insufficient magnetic field strength. Other NDE options are available. Eddy-current testing, which is commonly used in the inspection of nonmagnetic tubing, has high sensitivity to surface and near-surface defects. Ferromagnetic materials require a different approach because eddy currents have great difficulty penetrating beyond their surface; for these materials, the technique of magnetic flux leakage can be used to detect both surface and volumetric flaws. Three new inspection systems offering utilities improved flaw detection capabilities are described here—one based on magnetic flux leakage for heat exchanger tubing and two based on eddy currents for rotor bores and turbine blades.

Magnetic flux leakage for ferromagnetic tube inspection

Utilities have employed various methods for field evaluation of heat exchanger tubes—visual inspection, ultrasonic testing, hydrostatic testing, acoustic and halogen leak detection, and destructive testing—but the information obtained by these methods is usually limited and sometimes expensive. In recent years eddy-current testing has emerged as a reliable inspection technique for heat exchanger tubing made of nonmagnetic materials. However, magnetic materials (e.g., carbon steel) are widely used for tubing in power plant feedwater heaters, and special ferritic stainless steels (e.g., 29-4C, 439, E-Brite, Sea-Cure) are being used in condensers, feedwater heaters, and other auxiliary heat exchangers. The highly ferromagnetic properties of these materials severely limit the application of standard eddy-current methods.

Some modified eddy-current techniques have been tried on ferromagnetic materials, with mixed results. One involves magnetic saturation of a tube by pulsed, high-amperage direct current. This method can produce eddy currents throughout the tube wall, but it has several drawbacks, including the need for probe cooling during inspection, the possibility of false indications because of variations in permeability, difficulty in detecting gradual tube thinning, and complicated probe design. Another attempted solution, the remote-field eddy-current technique, is based on detecting the small fraction of eddy currents not confined to the surface of the test piece. It has good sensitivity to gradual wall thinning. For the technique to be equally sensitive to localized damage, however, the probe must have several small pancake coils on its circumference; thus it is delicate and expensive and requires sophisticated electronic interfacing.

For reliable in-service inspection of ferromagnetic tubing, a technique must be able to (1) inspect heat exchanger tubes from the inside; (2) accurately detect and size tube damage, both internal and external, both gradual and localized; (3) determine the point of damage origin, internal versus external; (4) distinguish between damage signals and nondamage signals, such as those from support plates; (5) inspect rapidly and require minimal operator interpretation; and (6) have instrumentation that can withstand field conditions. In response to this inspection need, EPRI has developed magnetic flux leakage equipment (RP1865-6). This method was chosen because of its simplicity, low cost, and proven performance in industrial applications.

The principle of flux leakage as applied to ferromagnetic heat exchanger tubing is illustrated in Figure 1. The probe, containing a magnetizing circuit and two sensors—one for localized flaws and the other for gradual wall thinning—is inserted into the tube. When the tube segment is magnetized to a certain level (full saturation is unnecessary), internal or external discontinuities produce localized perturbations of the magnetic field. Such perturbations produce signals that can be amplified, recorded, and displayed later for evaluation. Because the magnetic flux deeply penetrates the tube wall (whereas eddy currents lie mainly on the surface), the sensor can detect damage throughout the wall and can even distinguish internal from external damage.

This kind of technique is usually not adequate to detect gradual wall loss (such as wear, wastage, or thinning) because long and gradual defects do not produce suitable flux leakage. For this reason a Hall effect sensor is installed in the probe to measure the total magnetic flux through the tube wall and thus to show indirectly any gradual wall thinning.

Refined and optimized by extensive research, the technique has shown high sensitivity to small defects. For example, it easily detected an external wall loss of 10% in carbon steel tubing with an outside diameter of 0.750 in (19.0 mm) and a wall thickness of 0.087 in (2.2 mm). Such high sensitivity is now possible when the tube's inside diameter is at least six times its wall thickness, and research indicates the ratio can be reduced.

To demonstrate the technique's suitability for in-service inspection, several field tests were performed on tubes of various materials and sizes at Tampa Electric Co.'s Big Bend station, Duke Power Co.'s Marshall station, and Virginia Power's Yorktown station. The tests confirmed the technique's reliability, sensitivity, and repeatability; also, the mechanical probe proved to be rugged in operation.

The qualification tests at Duke Power demonstrated the equipment's ability to detect and characterize a wide range of defect types. In a blind test the system was used to inspect 21 carbon steel tubes containing 90 naturally occurring and artificial (machined) defects, including fretting of the outside wall, cracks, through-wall holes, and machined flats and notches of various depths. The system detected 86 of the 90 defects. The only features missed were shallow longitudinal machined notches with a maximum depth of 30% of the wall thickness. In most cases the defect depth was determined to within ±10%.

In the final version of the instrument, signals are displayed on a cathode-ray tube for interpretation. They can also be recorded and stored on magnetic tape or a paper strip chart. Scientific Technologies, Inc., the contractor, will commercially offer this instrument under the name Steeltest.

Eddy-current techniques for rotor bores and turbine blades

The most common inspection method for ferritic turbine generator rotor bore surfaces is magnetic particle testing. This technique has certain drawbacks, however: it is subjective, depending on the test operator's skill and diligence in identifying test indications, and thus suffers from poor repeatability. Automation would improve repeatability but cannot be easily implemented because the data are in the form of drawings, photographs, and verbal descriptions of the indications. Eddy-current inspection has potential for replacing magnetic particle methods in this application. Eddy-current tests can be readily automated because the data are in the form of voltages, which can be recorded, digitized, and manipulated by a computer.

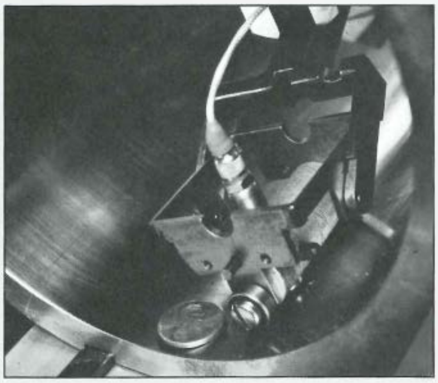
Under RP1957-5 General Electric Co. is developing an automated rotor bore surface inspection system based on a ferrite-core eddy-current transducer (Figure 2). The signals indicating the distance between the transducer and the bore surface are digitized every 0.2° as the sensor traverses the bore. The amount of data is kept manageable by a processing algorithm that selects the data to be stored.

A rotor section containing hydrogen flake cracks is being used to obtain test data. Detailed comparisons between eddy-current and magnetic particle test indications are being conducted to optimize the parameters of the eddy-current test. The project goal for the new system is to achieve a size detection capability equivalent to that of magnetic particle testing but with substantially improved repeatability. In addition, by eliminating the rotor surface preparation, demagnetizing, and retesting requirements of magnetic particle methods, the eddy-current system promises to reduce inspection time by one to two days.

A related effort is nearing completion on an improved eddy-current sensor for application to turbine blade airfoils and to valves and pipes. Two disadvantages of eddy-current testing relative to other NDE methods are its dependence on multiple scans by a single-element probe and the need for specialized probes when inspecting complex or irregular geometries. These often result in longer inspection times and more costly equipment.

To improve the inspection time and versatility of a conventional single-element hand-wound probe, EPRI and Failure Analysis Associates have introduced a flexible eddy-current coil array sensor (RP1957-4). The sensor consists of an array of spirally wound pancake coils photoetched on a mechanically flexible substrate. Each spiral element is designed to produce the needed electrical performance characteristics while the flexible substrate provides the mechanical strength and geometrical layout for the array.

Figure 2 This new eddy-current sensor for turbine generator rotor bore surfaces promises improved flaw size sensitivity, greater repeatability, and reduced inspection time relative to conventional magnetic particle testing.



The array is driven by a portable, microcomputer-based eddy-current instrument capable of dual-frequency operation. The software is quite general, permitting the inspection device to be used for many plant applications. The array is coupled to the instrument by a multiplexer capable of driving up to 1600 channels. The individual array elements can be addressed in any sequence defined by the software. A host utility is being sought for a field test of the prototype system during 1987.

Other developments

Future NDE work will investigate improved methods for detecting and quantifying creep fatigue and temper embrittlement damage in turbine rotors. Useful correlations are being developed to predict fracture toughness on the basis of hardness measurements, Charpy impact testing of miniature specimens, chemical analysis, and microstructural features identified from plastic replicas or surface impressions. The onset of thermal fatigue in high-pressure-rotor surface grooves may be detectable by hardness measurements and by X-ray line-broadening measurements. Temper embrittlement damage in low-pressure rotors is primarily caused by the segregation of certain impurities and alloy elements to the grain boundaries in the steel. Chemical etching and electrochemical tests are being explored for the analysis of grain boundary constituents.

Many of the techniques EPRI is investigating were presented at a seminar-workshop on fossil fuel power plant inspection held in September. The proceedings will be published early next year as an EPRI report. *Project Managers: John Scheibel and Stephen Gehl*

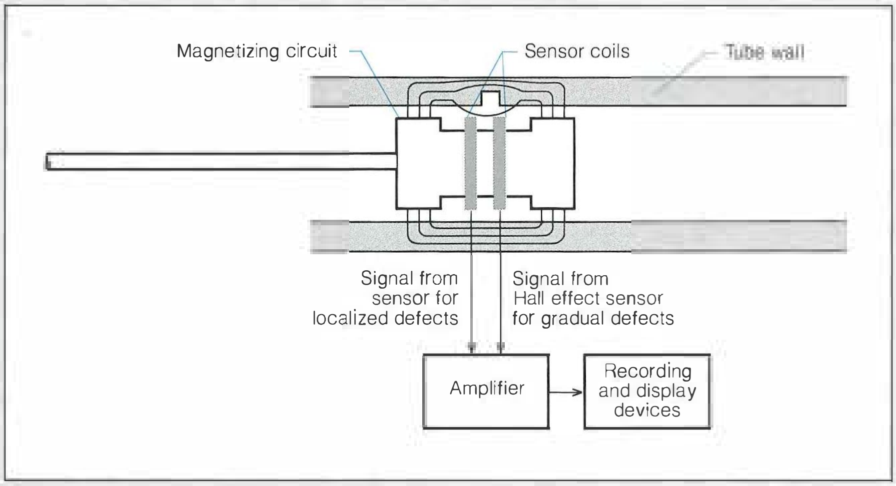


Figure 1 Magnetic flux leakage equipment has been developed for detecting internal and external defects and gradual wall thinning in ferromagnetic feedwater heater and condenser tubing. Material discontinuities cause perturbations of a magnetic field produced by the probe; the resulting signals are amplified, then displayed on a cathode-ray tube and/or recorded on magnetic tape or a paper strip chart. Successful field tests have been performed at three utilities.

R&D Status Report
ELECTRICAL SYSTEMS DIVISION

Narain G. Hingorani, Vice President

OVERHEAD TRANSMISSION

Optimized tower spotting with dynamic programming

One of the major objectives of RP2151, transmission line optimization, is to develop and implement a tower spotting computer program. The three major decisions affecting transmission line cost are structure type selection, conductor selection, and tower spotting.

Structure type selection is usually a result of experience or some external constraint. The decision is hardly ever a purely economic one. Conductor selection can be a fairly complex economic decision. EPRI has developed and distributed the computer program TLOP, which makes this chore easy. The third factor, tower spotting, requires selecting height, type, and location of transmission structures along a given alignment to meet certain topographic requirements and to keep construction costs to a minimum. The location and height of towers are selected from a set of predetermined discrete values so as not to exceed allowable loads and to equal or exceed a minimum clearance between conductors and the ground.

The conventional method of tower spotting is a graphic solution that has two basic shortcomings. First, graphic solutions require long and tedious calculations and rely heavily on the skill, experience, and judgment of the designer. Second, graphic solutions are often not minimal-cost solutions. In fact, finding a feasible solution is in itself quite a challenge when using graphic methods.

Unlike the graphic method, tower spotting by computer is based on a mathematical optimization model for obtaining a solution that is both feasible (meets the topographic requirements) and optimal (minimal cost). Generally speaking, tower spotting programs fall into two types: global optimizers and local optimizers.

Global optimization programs are true optimizers requiring a dynamic algorithm. Although the concept of the dynamic program is not difficult to understand, its application in programming is quite complex. Dynamic programming for transmission lines is a multistaged decision process in which tower types, heights, and locations are selected to obtain an optimal design along a given right-of-way.

Local optimization programs are based on a mathematical simulation of the manual procedure, often referred to as the spot-and-reject technique. This method computes and tests conductor curves for clearance with a series of discrete points representing the ground profile. These computer solutions are limited in the number of trial combinations of towers and result in optimizing only short sections of line independently.

As part of RP2151, EPRI's contractor, Power Technologies, Inc., adapted a global optimization tower spotting program, TLSPOT, to the TLWorkstation.* It is designed to work with TLOP and other TLWorkstation programs. TLSPOT shares a common data base with all the other task modules in the TLWorkstation package and adds its output to that data base.

Future research will investigate the interaction, if any, between the conductor selection activity and tower spotting. Right now, these activities are separate. If an interaction is found, then strategy for iterating the whole process will be developed to simplify the total optimization process. *Project Manager: Richard Kennon*

Testing of in-service wood poles

High strength-to-weight ratio, easy assembly, and acceptable esthetics are among the reasons that wood is a popular choice for transmission and distribution line construction. Single-pole and multipole structures have generally performed satisfactorily; however, wood poles can and do lose strength from decay and other causes during service life. Consistent performance of a wood pole line depends on effectively monitoring the changes in the strength of in-service wood poles.

Utility transmission and distribution lines have more than 120 million wood poles nationwide, representing an industry investment of over $20 billion. The key to how well utilities can protect this investment in wood pole lines lies in the answers to the following questions.

- How strong are in-service wood poles?
- Can strength loss with time in service be quantified?
- Are current wood pole inspection techniques sufficient to monitor strength loss?

The in-service wood pole test program, which is part of EPRI research, may provide answers to these vital questions (RP1352). Researchers are testing poles removed from service at Colorado State University's structural laboratory in Fort Collins; the tests are cofunded by the individual utilities supplying the test poles, Engineering Data Management (EDM), and EPRI.

This project began in 1985 and has been extremely successful. By November 1986, 12 utilities had sent 448 poles to be tested as part of the in-service pole test program. Three species (southern pine, Douglas fir, and western red cedar) from 10 of the 12 U.S. climatic regions are represented in this extensive sample. The participating utilities paid to ship the poles to the laboratory and for the actual cost ($250) of testing each pole to destruction. EPRI and EDM shared the cost of nondestructive evaluation (NDE) and data reduction/correlation.

Utilities removed a representative sample of poles (approximately 25) from service for each species and age of interest. Before testing, each pole was characterized by its diameter at various points along the pole; its length and moisture content; and its treatment type, time in service, and pole class. In addition, each pole was subjected to a sonic NDE technique developed in RP1352-2 (*EPRI Journal*, June 1986, p. 49).

Deterioration in wood poles over time is similar in different regions having like geographic and climatic conditions. Studies conducted as part of RP1352 indicate that the properties of in-service wood poles could be expected to vary significantly among the 12 regions (Table 1). Limited pole testing by the utilities in each region provides information on the condition of poles in their systems. Because of the wide participation in the test program, data exist for

*TLWorkstation is an EPRI trademark.

approximately 80% of the United States. Each utility established its own local data base. In addition, correlations between the properties obtained in the destructive tests and the measured NDE parameters form the basis of the NDE–predicted strength. This calibrated NDE technique permits the quantification of the relationship between strength and age for all poles in a climatic region with little or no additional testing.

Each participating utility received a local data base that showed a plot of strength of wood transmission line poles versus time in service (Figure 1). Data on stiffness versus age were also furnished in a similar plot. Data for zero years in service were available through previous testing funded by EPRI. For each of the ages tested, a probability distribution was plotted to show the variability of the data. Test data indicate that variability increases with age, whereas the mean strength decreases with age. The strength distributions for other ages are very strongly influenced by the local climate; therefore, each of the climatic regions is represented by a different distribution of strength with age.

Testing has shown that a pole's appearance does not necessarily indicate its actual strength. In some cases, poles showing considerable decay and cracking and determined to be inadequate by visual methods were determined by actual tests to be sufficiently strong to remain in service. Conversely, some poles with no sign of deterioration and judged to be sufficiently strong by visual inspection were shown by test to be insufficiently strong to remain in service.

Quantifying a wood pole's actual strength at a given time and tracking its loss of strength with time in service are essential elements of an effective maintenance program. Current pole maintenance programs try to evaluate the extent of deterioration but cannot determine a pole's strength. These evaluation programs typically consist of a lineman armed with a hammer, screwdriver, and calibrated ear. Although some utilities employ more-sophisticated techniques to determine which poles should be replaced, the fact is that until now, no satisfactory method has been available for quantifying the strength of a pole in the field.

Because electric utilities use more than five million wood poles annually in the construction and maintenance of transmission and distribution lines at a cost of more than $500 million, any improvement in pole evaluation techniques can result in significant savings. The utilities participating in the EPRI in-service pole test program have taken an important step toward more-efficient wood pole management. By establishing an in-service wood pole data base for their systems and climatic regions,

Table 1
CLIMATIC REGIONS FOR FIELD POLE TEST PROGRAM

Climatic Region	State/Location
Pacific Northwest	Western Washington, western Oregon, northwestern California, Sierra Nevada
Inland empire north	Southeastern Washington, eastern Oregon, southern Idaho, northern Nevada, Utah
Southwest	Southern and southeastern California, southern Nevada, Arizona, New Mexico, southeastern Utah
Northern Rocky Mountains	Northeastern Washington, northern Idaho, western Montana, northwestern Wyoming
Southern Rocky Mountains	Southern Wyoming, Colorado, northern New Mexico, Wasatch Mountains
Northern plains	Eastern Montana, North Dakota, South Dakota, eastern Wyoming, Nebraska
Southern plains	Eastern Colorado, Kansas, Oklahoma, northern and western Texas
Great Lakes	Minnesota, Iowa, Wisconsin, Michigan, northern Illinois, northern Indiana, Ohio
Gulf states	Eastern Texas, Louisiana, Mississippi, Alabama, Florida, Georgia
Atlantic coast	South Carolina, North Carolina, Virginia, West Virginia
New England	Maryland, Pennsylvania, New York, New Jersey, Connecticut, Rhode Island, Massachusetts, Vermont, New Hampshire, Maine

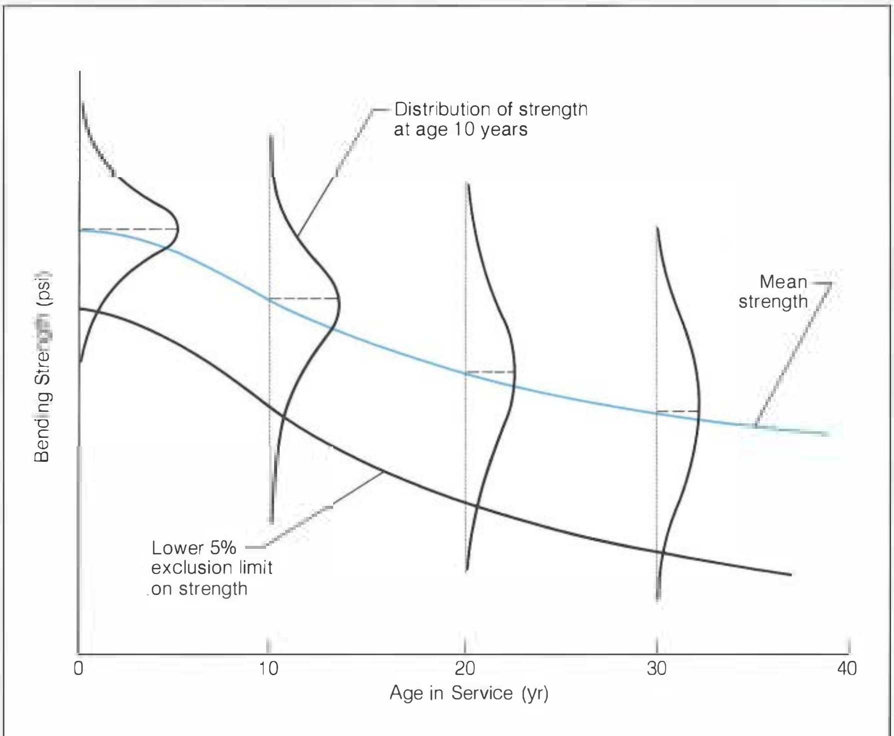


Figure 1 The probability distribution of strength can be plotted for wood poles for each of the ages tested. The bell-shaped curve becomes broader with age, and the mean strength is reduced. The strength distribution is strongly influenced by climate, so a different set of curves is plotted for each climatic region.

these utilities now have a better way to identify poles that actually need replacement and thus to minimize wood pole replacement costs. *Project Manager: Paul Lyons*

POWER SYSTEM PLANNING AND OPERATIONS

Improved EMTP

The electromagnetic transients program (EMTP) is a general-purpose computer program for simulating high-speed transient effects in electric power systems. The program features an extremely wide variety and range of modeling capabilities used to simulate electromagnetic and electromechanical transients ranging from microseconds to seconds in duration.

The program, which reproduces the functions of a transient network analyzer (TNA), has a wide range of important applications.

- Switching surge analysis
- Lightning surges, including backflash
- HVDC and static VAR controls, transients, and harmonics
- Ferroresonance and other resonance problems
- Shaft torsional oscillation, motor starting, or synchronizing problems

This program, developed by Bonneville Power Administration (BPA), was distributed worldwide. More than 150 utilities, manufacturers, universities, and laboratories are currently using the program.

To foster continued EMTP development and use, a development coordination group (DCG) was formed. BPA, the Canadian Electrical Association, the Institut de Recherche de l'Hydro-Québec, Ontario Hydro, the U.S. Bureau of Reclamation, and the Western Area Power Administration are members. ASEA and the Central Research Institute for the Electric Power Industries in Japan are associate members. EPRI and Electricité de France are working in cooperation with DCG to improve EMTP's documentation, modeling capabilities, and ease of use (RP2149).

An improved EMTP, Version 1.0, is an extensively tested and enhanced version of the M39 program distributed earlier by BPA. Because EMTP, Version 1.0, is a proprietary product of DCG and EPRI, it is available only under license. The code is available for VAX, PRIME, IBM–VM, IBM–MVS, and Apollo computers.

A wide variety of EMTP documentation is available, and more is being developed that is especially designed for both new and experienced EMTP users. Inexperienced users can study the basic principles and program use in the EMTP Workbook (EL-4651). The EMTP Primer (EL-4202) contains more complex topics, and the EMTP Application Guide (EL-4650) describes advanced topics and EMTP subtleties.

The revised Rule Book (EL-4541) explains EMTP input syntax and usage conventions. The EMTP source code itself is documented in EL-4652. A brochure on the broad application of the program (BR ESD 7, 8, 86) is available.

Researchers are now developing a Version 2.0 of the EMTP that will simplify input preparation, add to and improve the models available, and simplify program use. Version 2.0 is planned for release in late 1987. *Project Manager: James V. Mitsche*

Fast voltage estimation methods

Electric utilities are accustomed to planning and operating transmission systems so that service is maintained even if facilities are unexpectedly lost. Computer simulation techniques are used to test the hypothetical loss of facilities (commonly called contingencies) to be sure that the thermal, voltage, or stability limits are not exceeded. Various efforts have been directed toward calculating all three types of limits. Thousands of scenarios must be tested, often in a very short time, so that suitable corrections can be made if a potential problem is identified.

Very fast testing of thermal limits has long been possible, but voltage calculation is too slow to be practical. Hence, fast voltage estimation is desirable for adequate testing of transmission plans and for monitoring and controlling transmission system operation. EPRI recently completed a project with the objective of developing and testing a method that will calculate voltages in large power systems 10 times faster than the fastest and most accurate available method (fast decoupled power flow). Target accuracy was a ±2% difference in per unit results compared with the more-accurate method (RP2148).

The researchers first evaluated existing and proposed methods to quickly estimate power system voltages. A combination of methods was chosen for adaptation, development, and testing. Taken together, the methods (performance index calculation, adjoint sensitivity, and the epsilon decoupled load flow) were designed to act as a series of screens, separating and matching the severity of the test to find the method best suited to the type of calculation. Each method was tested for its speed and accuracy on a 39-bus sample model and on a realistic 530-bus model.

Tests on small systems successfully demonstrated how these methods could significantly speed voltage analysis without significantly sacrificing accuracy. Tests on a large system were quite successful, but they pointed out areas to be improved before production application would be possible. Results indicate that with further testing and development by utilities, the above objectives of the project can be met or exceeded.

Research-grade software used for development and testing is available from the EPRI project manager. The two-volume final report (EL-4798) describes the methods and displays test case results. *Project Manager: James V. Mitsche*

TRANSMISSION SUBSTATIONS

Dc converter station grounding

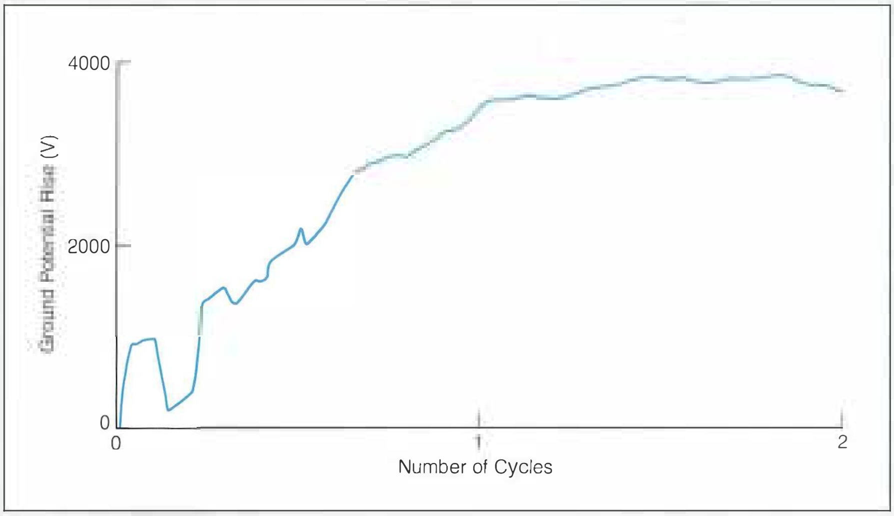
EPRI has developed two computer programs for the design of safe grounding systems and will add a third one for dc converter stations in mid 1987. This third computer program will calculate the ground potential rise during faults on either the ac or dc side of the converter station and will compute voltages at various points on a dc ground electrode operating in the monopolar, earth return, mode. The program's output will also include the calculated electric current density on the surface of the electrode elements, an important criterion to limit electroosmosis and possible failure of the electrode caused by soil moisture migration.

Utility interest in personnel safety for grounding systems focused initially on the ac substation, where workers can be subjected to step-and-touch voltages in the event of a nearby fault. Engineers first used approximate methods to analyze the voltage rise during faults, but they found highly accurate methods too complicated until the computer came into general use. Today, substation designers have an exact-method computer program called SGA (substation grounding analysis) that EPRI has distributed for several years.

Because transmission line fault currents were growing and public use of rights-of-way increasing, EPRI was asked to develop a program to analyze the safety aspect of transmission line grounding schemes; the result is the computer program GATL (grounding analysis of transmission lines).

Now that HVDC transmission is receiving much attention, utilities are requesting similar analysis capabilities for dc converter stations and for the associated remote dc ground electrode. In RP1494-6, Georgia Institute of Technology is developing the computer program CSGA (converter station grounding analysis), which is composed of two subprograms, DCGRND and AC/DCFLT. DCGRND will permit the designer to make a safety and operating analysis of the dc ground electrode during earth return operation. AC/DCFLT will calculate the voltages occurring during either an ac or dc fault. Interim report EL-4656 describes the development of a preliminary version of these programs.

Figure 2 A fault on the dc side of the converter station produces a waveshape containing dc, 60-Hz ac, and ac harmonics. This plot shows the voltage rise of the converter station ground mat in the event of a dc fault on the line side of the smoothing reactor.



A fault on the ac side of the converter station or on the ac lines feeding it is essentially the same as for a conventional ac substation. A fault on the dc side (Figure 2) presents a more challenging safety analysis because the ground potential rise will contain dc, 60-Hz ac, and ac harmonic voltages. Human tolerance to this waveshape has not been well researched; however, on the basis of available information, EL-4656 suggests a method for safety analysis.

Most major HVDC lines are designed to continue operation at a reduced level even if one polarity (or pole) is faulted. Such operation is accomplished by using the earth as a return conductor. Extensive grounding elements, called dc ground electrodes, are installed near the two terminal converter stations, and the dc current is circulated through the earth by these electrodes. EPRI final report EL-2020 details the design of these electrodes and has complete design and operating statistics on virtually all dc ground electrodes outside the Soviet Union.

By using computer program DCGRND, the electrode designer will be able to compute the electric current density on the surface of each electrode element. This calculation is important because the phenomenon of electroosmosis is the main cause of electrode failure. In electroosmosis, moisture in the soil migrates away from the electrode; the soil increases in electric and thermal resistivity; and the electrode can fail. Experimental data indicate that if the current density can be kept below 50 $\mu A/cm^2$, electroosmosis is negligible.

Computer program CSGA is complete in preliminary form and is currently being upgraded for distribution. After prerelease testing in early 1987, utility designers will have a tool capable of performing a complex analysis of the converter station grounding grid and the remote dc ground electrode. *Project Manager: John Dunlap*

Power transformers with amorphous alloy cores

Amorphous alloys promise to reduce core losses in power and distribution transformers by a factor of three compared with the best grain-oriented steel commonly used today. The value of these losses nationwide is immense, and several projects over the last eight years aim at making amorphous alloy cores a commercial reality.

One step in that direction will be taken when Niagara Mohawk Power Corp. energizes the first power transformer with an amorphous core, a 500-kVA unit in Syracuse, New York. Field experience over the next several years will establish this achievement's practicality.

The core of this pioneer transformer has laminations that are less than 0.001 in (0.025 mm) thick. In comparison, the most common steel laminations now used commercially are more than 10 times thicker. The thinness is a necessary outcome of the production process: to prevent crystallization, the molten alloy is ejected in a thin layer and cooled so rapidly that the normal atomic lattice cannot form. The result is an irregular atomic structure, termed amorphous.

The thin material has a small advantage in that thin laminations have low eddy-current losses, but the difficulty of handling the material and the need to cut and stack so many more laminations outweigh this advantage. Consequently, EPRI sponsored research to determine whether increasing the ribbon thickness by a factor of two or three would be possible (RP1290-3). Allied Signal Co., the world leader in amorphous alloy production, was able to produce amorphous ribbon with advantageous magnetic properties at thicknesses exceeding 0.0025 in (0.064 mm). However, the company was unable to maintain simultaneously such mechanical properties as brittleness within the acceptable range.

The investigation of this path has been halted because a different approach seems much more promising. Under RP2236-1, Allied Signal has scaled up a consolidation process in which several ribbons are superimposed and consolidated into a loosely bonded material called Powercore strip. During the two-year duration of this contract, significant progress has been made in increasing the width of the strip from 2 in (51 mm) to 4 in (102 mm) and to 6 in (152 mm). Improved guiding techniques led to more-precise registration of the layers, but some form of edge treatment is still necessary to guarantee the consistency and precision required of transformer core laminations. A slitting process has been demonstrated, and work is progressing on achieving high-quality edges. The number of plys or laminations has progressed from six to nine.

Under another contract Westinghouse Electric Corp. is developing techniques for using the Powercore strip commercially and is demonstrating a semiautomated cutting and stacking line (RP2236-2). A key part of this contract is to build and test corelets. These cores are made with variable geometry or technique with test windings for evaluation but without the insulation, power windings, tank, or oil that a complete transformer would require.

Corelets allow exploration of more options within the budget and resource constraints of the project. When the corelet size reached that of a 2500-kVA transformer, researchers found that the Powercore strip was sensitive to pressure and stress that could adversely affect its magnetic properties.

This discovery prompted a study of the material and yielded a production technique that improves the flatness of the strip and greatly reduces its sensitivity to pressure and stress. Pressure will probably still affect the laminations in a power transformer and result in some core losses, but researchers expect the strip to be a significant advance over the best steel.

On the commercial front, Allied Signal has announced that it will build a factory with an annual capacity of 60,000 t of amorphous alloy. Initially the company will serve the market for distribution transformer core material, but gains in uniformity, yield, and other parameters will also benefit power transformers. *Project Manager: Benjamin Damsky*

R&D Status Report
ENERGY MANAGEMENT AND UTILIZATION DIVISION

Fritz Kalhammer, Vice President

ANALYZING RESIDENTIAL CONSUMERS' ENERGY DECISIONS

As utilities increasingly turn to demand-side planning, assessing how consumers accept various end-use technologies becomes crucial. The degree to which consumers are likely to purchase these technologies depends in large part on their willingness to trade off tomorrow's savings in operating costs (the result of greater energy efficiency) against today's investment in higher capital cost. This willingness is commonly measured by a discount rate factor. A recent EPRI project addressed a number of qualitative and quantitative issues regarding consumer discount rates in an analysis of residential consumers' energy decisions (RP2547). One of the project's key findings is that the discount rate varies widely, depending on the circumstances surrounding a decision, and thus should be used with great caution in forecasting technology adoption.

A typical characteristic of many end-use technologies, such as electric heat pumps, is greater energy efficiency at a somewhat higher initial capital cost. In trying to foresee how well such technologies will be accepted, analysts have incorporated discount rates as key parameters in some utility load-forecasting models and in many engineering-economic assessments of market penetration. However, there is considerable controversy both about the concept of discount rates and about what empirical values most accurately represent actual consumer behavior.

Some of the controversy arises from different definitions of the term *discount rate*. In public policy analysis, discount rates are often used to represent the cost of capital in cost-benefit analyses conducted from a societal perspective. In a typical application of this kind regarding the utility industry, the discount rate is used as a normative tool to identify socially desirable levels of investment in conservation technologies. Assumed discount rates in such applications are typically quite low, reflecting the long-term societal perspective.

In forecasting and demand-side program assessments, the term refers to an assumed criterion that consumers use in deciding to invest in cost-saving technologies. The discount rate in this sense is a predictive tool used to forecast the penetration of new and existing technologies in real-world markets. In some cases the appropriate discount rate could be some measure of consumer cost of capital, such as the interest rate on a short-term loan; however, it is generally accepted that for predicting customer acceptance of a particular end-use technology, the cost of capital does not accurately represent consumer behavior.

Energy modelers have calculated the implicit returns on investment that consumers have required historically in purchasing end-use technologies. These implicit discount rates are seen as summarizing an amalgam of market forces that determine consumer choices. These forces include consumer preferences in trading between current costs and future savings, consumer assessment of risk, the lack of complete information, and credit constraints. Implicit discount rates are an indicator of the market acceptance of a technology: high rates imply market barriers and thus poor acceptance, and low rates imply few barriers and more ready acceptance.

Previous sources of implicit discount rates show a wide range of estimates. In a 1982 DOE economic analysis of proposed appliance efficiency standards, the estimated discount rates ranged in magnitude from 13% for electric clothes dryers to over 100% for electric and gas water heaters. Other empirical studies of discount rates implicit in residential equipment purchases—including those supporting the development of REEPS, EPRI's residential end-use energy planning system (RP1918)—have obtained estimates of 2% to 67%. In an analysis of building thermal shell investments (RP-1587), the estimates ranged from 3% to 87%, depending on homeowner income and age.

Discounts implicit in conservation actions

Given the importance of implicit discount rates in some forecasting models and their widespread use in analyses of the market potential of energy-related durables, the EPRI research under RP2547 was designed to estimate these rates for various equipment choices and to evaluate their usefulness in forecasting. The project, conducted by Cambridge Systematics, Inc., and Charles River Associates, Inc., has focused on the discount rates implicit in household decisions to adopt conservation measures and purchase high-efficiency appliances.

In the data analysis, a behavioral model was formulated to describe the consumers' choice problem. The model is based on the observation that there exists a range, or distribution, of discount rates in the population. A given household will adopt a conservation measure if the household's discount rate is less than the rate offered by the measure (i.e., the return on investment is greater than some threshold). Household discount rates vary because of differences in such observable characteristics as income, age, and education, as well as for unexplained idiosyncratic reasons. The proportion of households adopting a measure depends on the distribution of discount rates in the population.

Given an assumption about the general shape of a distribution of discount rates, then its mean, variance, and other parameters can be estimated statistically from data on consumers' actual decisions. This statistical estimation requires information on the estimated rates of return of prospective investment options and the corresponding household choices, as well as on socioeconomic attributes and other factors that affect the decision. Few such data sets exist because of the difficulty of identifying the costs and savings of prospective measures, particularly those rejected by households. The home energy audit and low-interest conservation financing programs widely implemented by electric utilities represent a promising source of such data. One drawback of data collected in conjunction with these programs, however, is that the audit information and financial incentives may distort the rate of return as a factor in the decision.

Data collected previously for two home energy audit programs were analyzed in this study. The first was a program offered by Pacific Gas and Electric Co. (PG&E) to its residential customers between 1979 and 1985. In conjunction with a home inspection that evaluated over 30 prospective conservation measures, PG&E offered zero-interest financing for some of the measures. The second program was a pilot weatherization program conducted by the Bonneville Power Administration (BPA) between 1980 and 1982. BPA also offered zero-interest financing for recommended measures in conjunction with its audits. Under both programs data were collected on the conservation measures evaluated in each audit, their estimated costs and savings, and whether the household actually implemented the measures.

The BPA program also collected data on a control group of unaudited households and the conservation measures they adopted. These data provided the added opportunity to analyze factors that influence whether a household requests an audit. It is expected that requesting an audit and adopting conservation measures are closely related decisions, and that households with lower discount rates are more likely to request audits.

Major findings

For the conservation measures financed with zero-interest loans in the two programs, the auditor-estimated rate of return on investment was not a significant factor in explaining adoption—even though the loans must be repaid at some future date. Thus the financing option appears to overwhelm the other consumer trade-offs and prohibits the estimation of discount rates for the measures involved.

For the PG&E audit recommendations not covered by zero-interest financing, the estimated average discount rates implicit in customer choices were generally very large; they ranged from almost 40% for wall insulation to over 300% for clock thermostats (Table 1). In contrast, for those households in the BPA program that did not request energy audits, the estimated average discount rate for a set of weatherization measures was nearly 400%, suggesting that the informational value of audits alone substantially reduces discount rates (increases acceptance). These high values illustrate the point that the implicit discount rate captures an amalgam of factors influencing consumer choice. Only if these factors can be isolated and accounted for in an analysis can estimated discount rates be considered a measure of the consumers' financial cost of capital. Note also that these high rates are in fact consistent with the relatively low adoption rates in that the average discount rate in this study represents the rate of return that must be offered in order for half of the consumers to adopt a measure.

Table 1
IMPLICIT DISCOUNT RATE RESULTS FROM PG&E DATA

	Average Rate	Range of Rates*
Wall insulation	40%	0–84%
Clock thermostat	308%	111–506%
Replacement furnace	68%	42–94%
Solar water heater	100%	46–154%

*Represents one standard deviation.

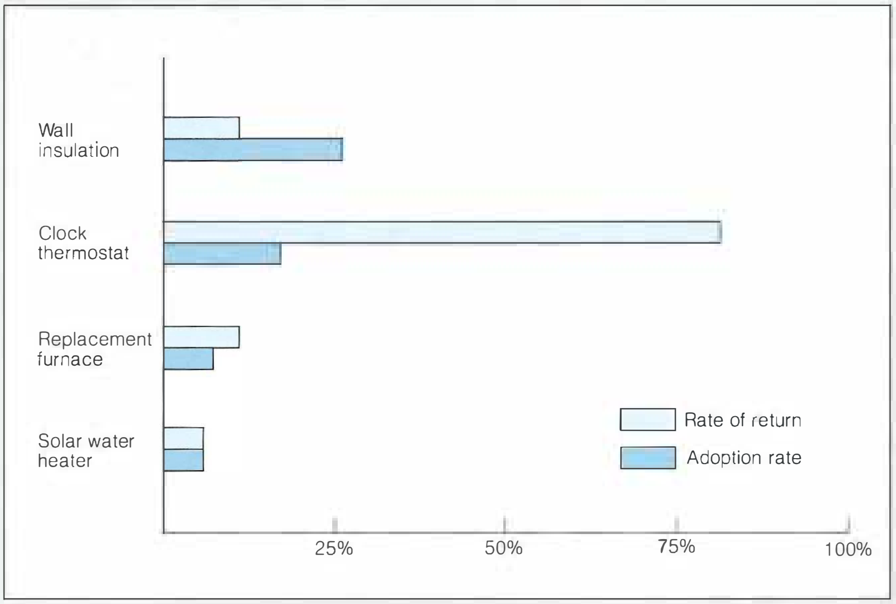
Although the estimated implicit discount rates were generally high, they do appear to reflect an important determinant of household decisions to adopt measures. The expected rate of return on investment, as calculated by the auditor, was a statistically significant factor in explaining adoption for four of the five measures not available for financing in the PG&E program (Figure 1).

The BPA data indicated that the decision to request an audit depended significantly on dwelling size, attitudes toward conservation, and the attractiveness of the conservation measures. The strong association between audit requests and the attractiveness of conservation measures suggests that households who believe that certain measures are desirable use audits as a means of confirming those beliefs.

In summary, the study found a wide range of discount rates, both with respect to a given measure and across measures. This indicates that discount rates are quite sensitive to the measure and the population under consideration. As a result, they must be used with great caution in long-term forecasting models or assessments of market potential for residential demand-side programs. Models that use discount rates in a life-cycle-cost formula to forecast customer acceptance without recognizing other factors that influence choice probably oversimplify the decision process. Still, implicit discount rates and the analytic techniques for estimating them are useful tools in evaluating the relative importance of costs, savings, information programs, and financing as incentives to promote specific consumer actions.

An implication of the study for future research is that more effort should be made to identify the unobservable factors that appear to influence consumer behavior toward energy choices, factors that are lumped together into the discount rate in analyses focusing primarily on capital and operating costs. EPRI is sponsoring a project on customer preferences and behavior that promises major advances in this area (RP2761). *Project Manager: Steven Braithwait*

Figure 1 Auditor-estimated rates of return and consumer adoption rates for four measures evaluated in a PG&E residential conservation program. These measures were not covered by the program's zero-interest financing provision.



R&D Status Report
ENVIRONMENT DIVISION

Stephen C. Peck, Acting Director

OUTDOOR AIR POLLUTION AND HEALTH

Very high levels of community air pollution involving sulfur oxides and particulate matter have been associated with adverse effects on human health. Most of the evidence for this association dates from 20 to 30 years ago, when air emissions were relatively uncontrolled and there were extreme pollution events as a result of long periods of air inversion. Such events as the Donora, Pennsylvania, pollution incident of 1948 and the London fogs of the 1950s and 1960s generated public pressure to improve outdoor air quality, which in the United States culminated in passage of the Clean Air Act Amendments of 1970. Even though levels of sulfur dioxide (SO_2) and total particulate matter have declined markedly since that time, some believe that community air pollution (as measured by these or other pollutants) may still be a cause of respiratory illness. However, there have been few attempts to link recent air quality conditions with adverse health effects. The Harvard Study of Air Pollution and Health, also known as the Six-Cities Study, has been addressing this information gap since 1974. A major undertaking, the study is sponsored by the National Institute of Environmental Health Sciences, the Environmental Protection Agency, and EPRI (RP1001).

The Six-Cities Study is probably the most important epidemiologic study of air pollution currently in progress in the United States. It focuses on potential health effects from chronic exposure to air pollutants, effects that are by nature difficult to detect, and thus requires following a large population for an extended period. Although the study was designed primarily to investigate the possible adverse effects of contaminated ambient outdoor air, a sizable component is devoted to indoor air quality, both because of the potential confounding effect of exposure to certain indoor pollutants and because of an independent interest in the health effects of such exposure (*EPRI Journal*, September 1984, p. 45).

For the study, population samples of both adults and children were selected at random in each of six communities in the eastern and midwestern United States: Watertown, Massachusetts; Kingston and Harriman, Tennessee; Steubenville, Ohio; St. Louis, Missouri; Portage, Wisconsin; and Topeka, Kansas. These cities were chosen to represent a range of anticipated pollution exposure, from below to above the current federal primary air quality standards; selection was based on historical ambient outdoor air quality conditions and on changes in pollution levels expected to occur over the study period. Air quality monitoring and health data collection are ongoing in all six communities.

Air quality monitoring includes the measurement of total suspended particles (TSP), SO_2, nitrogen dioxide, ozone, size-fractionated suspended particulate matter, and the water-soluble sulfate fraction of TSP (TSO_4). A three-stage strategy combining fixed-location air sampling at a central site, indoor-outdoor monitoring, and personal monitoring is employed to assess exposure to pollutants.

The collection of health data entails annual examinations of participating children and triennial examinations of adult subjects. At each examination, a history of respiratory illnesses and symptoms is obtained by means of a standardized questionnaire (completed by a parent or guardian for each child); simple tests of pulmonary function are administered; and, for children, height and weight are measured. Additional information is gathered about socioeconomic status, tobacco smoking, occupational exposures, dwelling characteristics, and type of fuel used for cooking and heating.

The Six-Cities Study is a longitudinal investigation (i.e., one that follows changes in the health status of a population over time), and collection of the data necessary for the intended analyses has not been completed. However, certain comparisons among or across groups at a given time (cross-sectional analyses) can be made by using data available from the early years of the study. The investigators from the Harvard School of Public Health recently carried out such comparisons to determine whether community air pollution poses a threat to respiratory health in children.

Specifically, the investigators have described the association between the respiratory health of 10,106 children at their first and second annual examinations and the outdoor concentrations of TSP, SO_2, and (to the extent data are available) TSO_4 in each city during the years preceding these examinations. All the examinations took place between 1974 and 1980. The study participants included in these analyses were enrolled during one of the first three successive annual evaluations in each city and were between six and nine years old at their initial examination. Three periods of exposure were considered: the one-year period preceding an examination, the child's lifetime up to the date of examination, and the first two years of life.

At the first examination, a history concerning doctor-diagnosed respiratory illness before two years of age was obtained. At the second examination, the questionnaire responses were evaluated for the occurrence of five illness and symptom variables in the previous year: bronchitis; cough for three months of the year or more; wheeze occurring most days or nights or apart from colds; respiratory illness that kept the child at home three days or more; and a composite variable for lower respiratory illness (defined as the presence of either bronchitis, persistent cough, or a respiratory illness that kept the child at home three days or more). Pulmonary function was evaluated at each examination by using a water-filled recording spirometer to measure forced expiratory volume in one second (FEV_1) and forced vital capacity (FVC).

Nine air pollution regions were created by dividing each of three cities (St. Louis, Steubenville, and Kingston-Harriman) into two regions and treating the remaining three cities as single regions. In Steubenville and Kingston-Harriman, the regions were defined by topographic features and by the location of major air pollution sources; in St. Louis, they were defined by proximity to the major source of SO_2. The three years of participant enrollment in each of the nine regions defined 27 groups of children with different histories of exposure to community air pollution in the years preceding their first and second examinations.

The respiratory illness and symptom data were analyzed by using a two-step multiple-regression procedure. (The pulmonary function data were analyzed separately by using a different two-step multiple-regression procedure.) In the first step, summary respiratory health values for each of the 27 groups were derived. In the second step, these summary group values were examined for their relationship to the applicable mean air pollutant concentration; both the variation of health values between cities and that within cities were considered in the estimation process.

The between-city results revealed a positive association between mean TSP concentration in the previous year and rates for all five of the illnesses and symptoms recorded at the second examination. These rates were adjusted for age, sex, maternal smoking, and parental education, all of which are factors known to influence respiratory health in childhood. The association was statistically significant for cough (Figure 1), bronchitis, and the lower respiratory illness index. The same pattern of association was found in the analyses based on TSO_4 concentrations. With SO_2 concentrations, somewhat weaker associations were observed and only cough remained significant. The analyses using lifetime exposure data showed similar overall associations across the six cities, but no association was found for reported respiratory illness before age two.

Recognizing that the between-city associations may represent differences among the cities unrelated to community air pollution, the Harvard researchers also performed analyses to examine possible spatial and temporal covariation of illness and symptom rates and air pollutant concentrations in each city separately. Each such within-city analysis, of course, had many fewer than 27 sample points. These within-city analyses generally did not show results consistent with the between-city observations. Further, mean pulmonary function levels—which were adjusted for age, sex, height, maternal smoking, and parental education—were not associated with TSP, SO_2, or TSO_4 concentrations in either the between-city or within-city analyses. This was true for both the one-year and the lifetime exposure periods.

These findings from the Six-Cities Study are preliminary and must be interpreted cautiously. Although some of them suggest that exposure to moderately elevated concentrations of community air pollution may increase respiratory illness among preadolescent children, others do not, and much uncertainty still exists. Future analyses will focus on longitudinal measures of respiratory health derived from repeated examinations of the participating children as they move through adolescence, as well as on more sensitive measures of pulmonary function. *Project Manager: Cary Young*

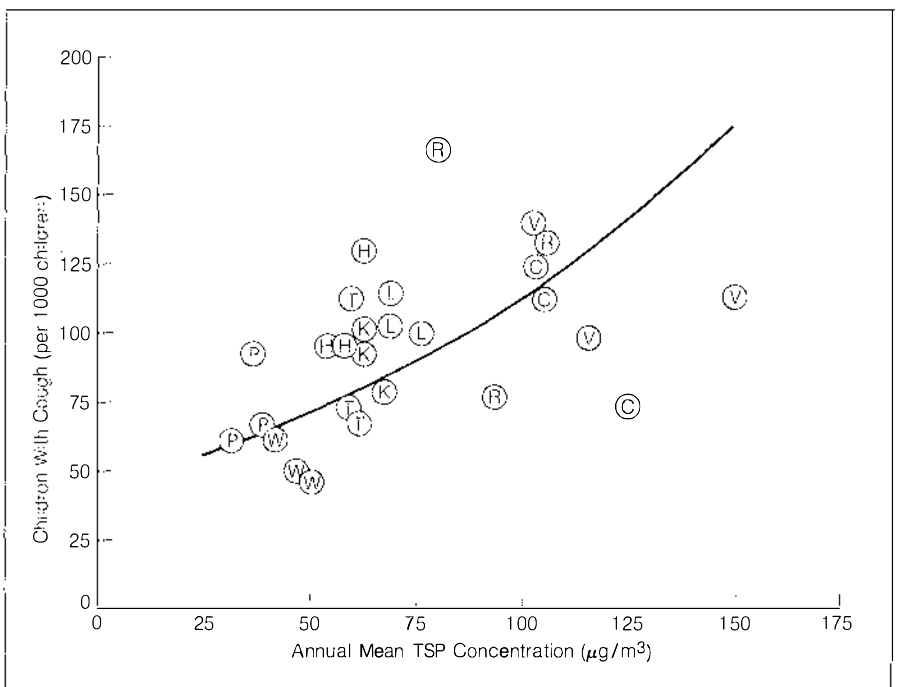


Figure 1 For each of 27 groups of children from the Six-Cities Study, the adjusted frequency of persistent cough at the second examination is plotted against mean TSP concentration during the previous year. The letters identify the nine geographic areas covered by the analysis: *C* and *L* for the two parts of St. Louis; *H* and *K* for Harriman and Kingston, Tennessee; *P* for Portage, Wisconsin; *R* and *V* for the two parts of Steubenville, Ohio; *T* for Topeka, Kansas; and *W* for Watertown, Massachusetts.

THE ROLE OF LOW-SULFUR COAL IN SO_2 REDUCTION STRATEGIES

The cost of low-sulfur coal is a critical parameter in utility decisions about how to reduce sulfur dioxide (SO_2) emissions to comply with proposed federal acid rain legislation or equivalent state initiatives. To improve our understanding of coal market risks, a series of EPRI research projects has examined not only coal supply but many other utility decision factors as well. The results enable better definition of the markets for scrubbing and novel clean-coal technologies, the industrywide costs of compliance, and the uncertainties that remain.

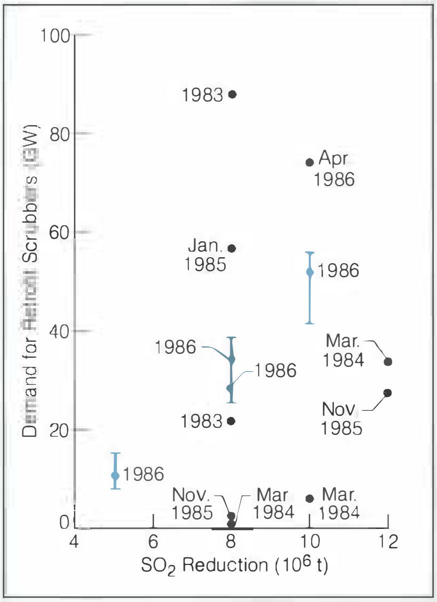
The picture for low-sulfur coal is complex and requires careful consideration of both supply and demand aspects. Recent estimates of the possible magnitude of switching from higher-sulfur to lower-sulfur coals under proposed legislation range widely, from 50 to 130 million tons a year. Analyses and projections of the magnitude of the other major conventional SO_2 reduction option, retrofit scrubbers for flue gas desulfurization (FGD), range from near zero to almost 90,000 MW; recent EPRI-sponsored estimates by Energy Ventures Analysis, Inc. (RP2369-53), fall in the middle ground (Figure 2). Better information about the specific quality, reserves, mining conditions, and costs of low-sulfur to very low sulfur coals is essential to support utility decisions and informed environmental policy. At the same time, a detailed understanding of utility compliance options provides both a focus and a motivation for such efforts.

Historical premiums for low-sulfur coal in the East

Resource Dynamics Corp. has compiled information about historical price premiums for low-sulfur versus high-sulfur coal that eastern utilities have experienced since 1972 (RP2369-51). One insight from this analysis is that premiums for low-sulfur coal have been very different in different regions and at different times over this period.

A second insight is that the term *premium* means very different things to different users. There is no universally accepted definition. A coal quality premium might measure the price difference between high- and low-sulfur coal either at the mine or as delivered to the power plant, or it may be an estimate of an increase in low-sulfur-coal prices alone under a demand surge. More complication comes from comparing contract purchases with spot purchases and from using different sulfur ranges

Figure 2 Since 1983 various organizations have estimated the demand for retrofit scrubbers under possible acid rain legislation. To reflect the diversity of utility conditions and cost trade-offs, the EPRI-sponsored estimates (color) were derived from site-specific analyses; they include ranges of uncertainty about the delivered price of low-sulfur coal.



to define low- and high-sulfur coal. Further, a premium can be created by a drop in the price of lower-cost coal (i.e., by the floor falling) just as much as by a rise in the price of higher-cost coal (i.e., by the ceiling rising). And as analysis has shown, a premium might develop between low-sulfur and very low sulfur coal as the demand for low-sulfur coal weakens and that for very low sulfur coal intensifies.

Considering statewide averages of delivered contract prices in the eastern United States, 1985 premiums per million Btu between very low sulfur (~0.7%) coal and medium-sulfur (2–3%) coal ranged from nearly zero in North Carolina to 40–50¢ in West Virginia, Alabama, and Illinois to $1.00 in Georgia and $1.50 in Indiana. In some areas the premium grew early and has subsequently diminished; in others it has changed little, or even surged, in recent years. Key explanatory factors include the idiosyncrasies of specific contracts and their escalation terms; geologic conditions and the constraints on productivity gains for low- versus high-sulfur mines; transportation distances, barge access, and other geographic considerations; and competing demands for low-sulfur coal from the metallurgical and export markets.

From this varied historical experience alone, it is easy to see why there has been such a wide spread in utilities' recent assumptions about low-sulfur-coal costs under acid rain legislation.

Reserves and potential supply of low-sulfur Appalachian coal

Recent EPRI research has by no means eliminated the uncertainties surrounding low-sulfur-coal supply, but it has shifted our attention to more specific questions where better information may be of the greatest value. The available evidence on reserves and production capacity reduces concern about the likely adequacy of moderately low sulfur coal (1–1.5% sulfur) and the magnitude or duration of a price surge; however, it raises concern about the uncertainties surrounding very low sulfur coal (0.7–1% or less) and coal with certain additional premium characteristics and their longer-term price behavior.

These conclusions were reached in a study by Charles River Associates, Inc., Skelly and Loy, and Boulder Exploration Group (RP2369-30). Drawing on coal production statistics, selected mine data, and coal company interviews, the study concluded that annual low-sulfur-coal production in the early years after a demand surge could be increased by 75–100 million tons from greater capacity utilization and by 20–60 million tons from expansion at existing mines. Another encouraging picture of short-term production capabilities was provided by the 1984 experience of Detroit Edison Co. in seeking low-sulfur coal in a slack market; in response to the utility's requisition, one of the largest that year, bids totaling approximately 75 million tons of low-sulfur coal a year were received from relatively large producers in the Central Appalachian region. An estimate of similar magnitude for near-term production capacity was reached by Temple, Barker & Sloane, Inc., in a 1984 study of coal market issues (EPRI EA-3750). However, all these estimates say nothing of the long-term production potential for low-sulfur coal. Nor do they eliminate concern over a surge in prices, although they suggest that such a surge may be shorter-lived than has been expected.

The need to reassess reserves to support long-term planning is strongly illustrated by two findings of RP2369-30: first, the observation that data on Appalachian coal reserves are insufficient to permit meaningful evaluation at sulfur cutoffs much below 1.4%, and second, profound disagreement with earlier work over the proportion of reserves thought to be surface-mineable. By applying modern mining engineering and economic principles to a sample of 24 reserve blocks—each 2 miles (3.2 km) square—in Kentucky, West Virginia, Virginia, and Pennsylvania, Skelly and Loy found that surface-mineable reserves almost matched underground-mineable reserves; in contrast, calculations using the methods applied by the Bureau of Mines for the Demonstrated Reserve Base showed underground reserves exceeding surface-mineable reserves by a factor of 2.3. If this small sample of blocks is a guide, the inadequacies of coal reserve information extend not merely to the quality of reserves but to the very concept of how they might be mined.

Table 1
FACTORS IN UTILITY SCRUB–SWITCH DECISIONS

Factor	Impact	Decision Favored
Near high-sulfur-coal production	Low transportation costs for high-sulfur coal	Scrub
Coal delivered by barge	Low transportation costs for low-sulfur coal	Switch
Cyclone boiler	Limited low-sulfur-coal options	Scrub
Small units	High FGD costs	Switch
New units	Long FGD lifetime	Scrub
Congested site	High FGD costs	Switch
Baseload unit	Low FGD costs	Scrub
Cycling unit	High FGD costs	Switch
Unit burns mid-sulfur coal	Small SO_2 reduction by switching	Scrub
High real discount rates	Low levelizing factor	Switch
Tax-exempt financing	Low FGD financing costs	Scrub
High corporate debt	Limited financing capability	Switch
Utility owns high-sulfur-coal mines	Low incremental cost for high-sulfur coal	Scrub
Increased rail competition	Lower transportation costs	Switch
High low-sulfur-coal prices	High switching costs	Scrub

Source: EPRI EA-4857, p. 13-12.

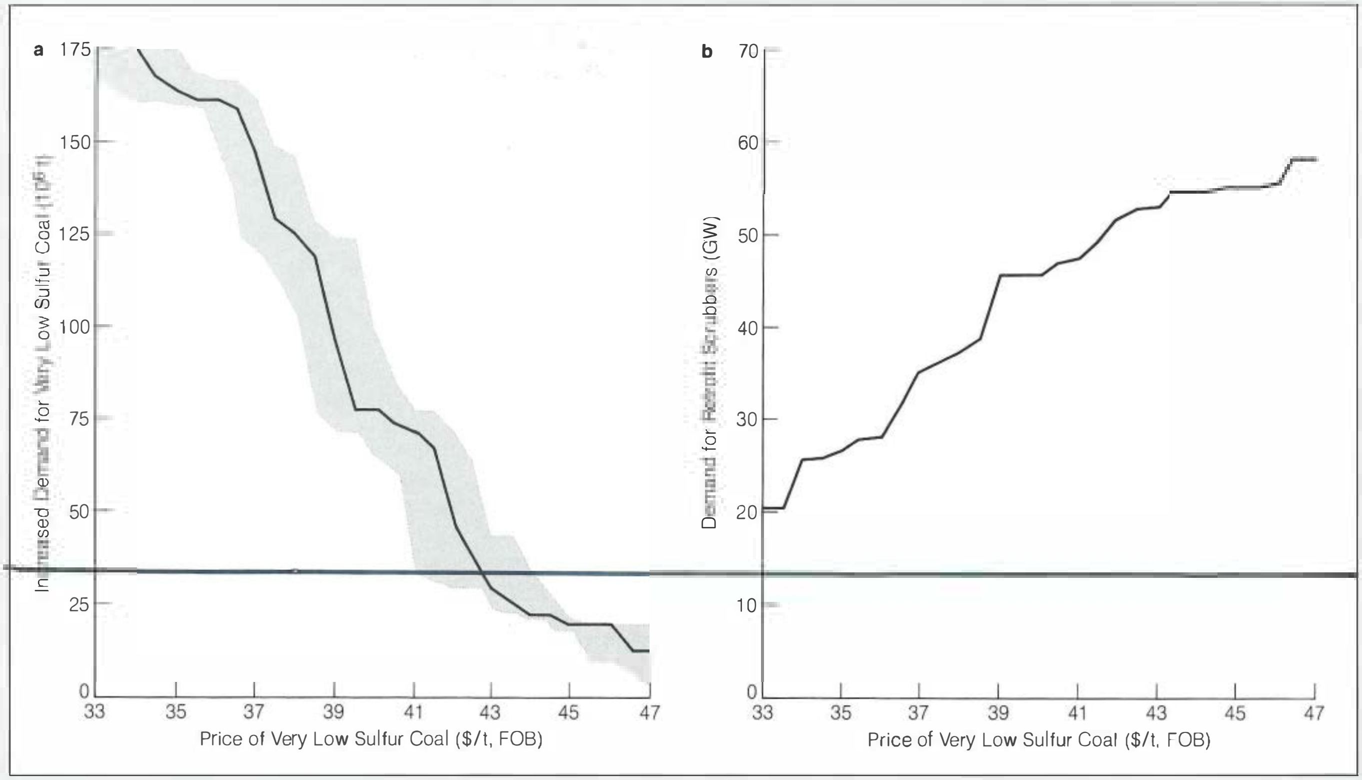


Figure 3 For a legislative scenario with a total annual SO_2 reduction of 10 million tons, an EPRI-sponsored analysis of eastern utilities estimated how the price of very low sulfur (~0.7% or less) Central Appalachian coal affects (**a**) the demand for that coal and (**b**) the demand for retrofit scrubbers. The coal demand is very sensitive to price, with scrubbers acting as a strong buffer to hold that demand down as price rises. (The uncertainty band indicates a ±$1/t shift in assumed transportation costs.)

Diversity of compliance decisions and coal market effects

A variety of factors will influence utility decisions on SO_2 emission reduction strategies. Table 1 presents some of these factors and their effect on the choice between coal switching and retrofit scrubbers. To provide insights on such decision factors, Energy Ventures Analysis—with support from Stearns Catalytic Corp. on engineering calculations and A. T. Kearney on coal transportation cost estimates—conducted a major study for EPRI of coal markets and utility fuel choices under three acid rain legislation scenarios (RP2369-53). The scenarios correspond roughly to total annual SO_2 emission reductions of 5, 8, and 10 million tons.

Unlike most studies, this project took a site-specific approach. Engineering cost estimates for installing and operating scrubbers or for switching to nondesign coals (involving modifications in grinding and particulate removal systems) were determined for virtually all candidate power plants in the 31 eastern states. Also, the existing and likely competitive environment for coal transportation was assessed for individual coal movements. These considerations were then weighed from a utility system perspective to estimate probable compliance strategies. In some cases, the least-cost strategy from this system perspective differs from that determined for individual power plants in isolation.

This study demonstrates how, in spite of the problems with coal supply information, significant insights into coal markets can be obtained from closely examining constraints on utility coal demand. In particular, a detailed knowledge of the costs and trade-offs among different compliance options at individual utilities and power plants presents a price target—in fact, a whole range of price targets—that low-sulfur coal must beat to be viable. Figure 3, for example, shows the outlook for very low sulfur coal and retrofit scrubbing in the high SO_2 reduction scenario.

The detailed picture of demand developed in RP2369-53 yields relatively low limits on the likely price ceiling for low-sulfur Central Appalachian coal, thus reducing concern over the coal's price behavior. The low price ceiling is a result of the competitive role of retrofit scrubbers and, to a much lesser extent, western coal. At the same time, the study highlights a worrisome shift in the coal market when, to achieve SO_2 reductions of 10 million tons or more, the demand for moderately low sulfur (~1%) coal nearly evaporates and that for very low sulfur (~0.7%) coal expands in its place. In this case, a price premium develops between the two.

The findings of EPRI's research into site-specific compliance options differ from earlier findings in important ways. For example, more scrubbing is projected than in most other studies (as indicated in Figure 2): scrubbing accounts for 30–47% of the SO_2 reduction at 5 million tons, 50–66% at 8 million tons, and 65–75% at 10 million tons, with switching to low-sulfur coals accounting for the rest. Shocks to midwestern high-sulfur-coal producers are mitigated by the attractiveness of scrubbing. Western coal receives only a negligible boost in any of the cases. Most important, the detailed analyses conducted in this project demonstrate the great diversity of costs among compliance options at any level of emission reduction.

This article is based on a paper prepared for a Senate staff briefing, "Fitting Low-Sulfur Coal Into the Compliance Equation," which is available from the EPRI project manager. The final report for RP2369-30, on low-sulfur-coal reserves and supply, has been published (EA-4710); final reports for RP2369-51 and RP2369-53 are forthcoming. *Project Manager: Jeremy Platt*

R&D Status Report
NUCLEAR POWER DIVISION

John J. Taylor, Vice President

PIPING INTEGRITY MATRIX

There are major incentives for improving the seismic design and pipe break criteria that are applicable to the design of nuclear piping systems. The conservatism that current industry practices required by NRC regulations introduce into the design of nuclear piping systems leads to an excessive use of snubbers, pipe whip restraints, and jet impingement shields. There is general agreement within the nuclear industry and the NRC that plant safety would actually be improved and that substantial cost savings would be realized if the numbers of these devices could be reduced. EPRI has supported research on piping integrity for a number of years. Recently, the issue was addressed by introducing matrix management to coordinate and apply the results of research being done in the various departments of EPRI's Nuclear Power Division. This report summarizes EPRI's contributions to seismic piping design and the evaluations of degraded piping.

Seismic piping design

The design of nuclear power plant piping must provide for two conflicting requirements. One is that the design permit relatively unrestrained pipe movement to accommodate thermal expansion and thus minimize thermal stresses; the other is that it restrain pipe motion to minimize seismic stresses should an earthquake occur. The need to satisfy these conflicting requirements, as well as tight schedule requirements and overly conservative design criteria for plant design and construction, has resulted in a proliferation of seismic snubbers in nuclear power plant piping. (A snubber is a device that depends on a mechanical or a hydraulic feature to provide restraint against rapid pipe motion, such as occurs during an earthquake. A properly functioning snubber allows for free thermal expansion and contraction of pipe during normal plant operation.)

Recent emphasis on improving the reliability of piping systems, the proliferation of requirements for the in-service inspection and testing of snubbers, and the problems that have been experienced with some snubbers have made it increasingly important that snubbers be used only where they are really needed. There are definite economic and reliability gains associated with limiting the number of these devices. Unnecessary snubbers adversely affect plant operability, outage management, accessibility, and the goal of keeping plant personnel radiation exposures as low as possible. Moreover, costs of inspection, maintenance, repair, and eventual replacement are considerable.

One of the benefits to be realized from using fewer seismic snubbers in nuclear power plants is the cost saving of the hardware itself. Many recently built nuclear plants use between 1000 and 2000 snubbers at costs ranging from $1000 to $10,000 each. Obviously, eliminating a major fraction of the snubbers in a new plant would yield a substantial saving. In addition, there are large costs associated with the careful installation that snubbers require, as well as with their in-service inspection and testing. Utility estimates of the average cost of a snubber during the lifetime of a plant range between $10,000 and $60,000. With about 48,000 snubbers installed in U.S. power plants, the lifetime cost of snubber maintenance is well over $1 billion.

Reducing the use of snubbers can also yield substantial indirect savings. Plant in-service inspection time would be reduced, reliability and maintainability would be improved, and the improved access would result in lower radiation exposure for maintenance personnel.

The recently completed guidelines study (NSAC-104) on the feasibility of reducing the use of snubbers put forth the following recommendations: (1) use PVRC damping values (code case N-411)—recently issued NRC caveats about this code case should be kept in mind; (2) combine all modes by using the method of the square root of the sum of squares; (3) when allowed by low values of thermal expansion, replace snubbers with rigid struts; and (4) use sophisticated and expensive techniques (e.g., independent support motion, time-history analysis) only when a snubber is difficult to inspect and maintain and hence justifies the analytic effort.

The snubber guidelines also provide limitations on how many snubbers can be removed before pipe support and nozzle loads, pipe displacements (interferences), and BWR hydrodynamic loads become excessive.

EPRI has also begun work on several tasks, the completion of which will provide maximum benefits to the utility industry in its attempts to reduce the number of snubbers installed in nuclear power plants. The objectives of these tasks are as follows:

- Develop guidelines, technical justifications, and criteria for snubber reduction methods for use in licensing submittals
- Develop the technical basis for NRC acceptance of damping values to be used for a range of frequencies (0–100 Hz)
- Develop generic in-service inspection snubber test criteria
- Develop uniform nozzle and support load criteria
- Demonstrate the application of alternative methods, such as energy-absorbing pipe supports, to replace snubbers
- Quantify current seismic margins
- Demonstrate the technology and get it to the utilities

Evaluation of cracked piping

Current regulations require that nuclear power plants be designed and built to ensure that they can be shut down safely in the event of sudden circumferential or longitudinal breaks. This extends to and includes double-ended guillotine breaks in high-energy fluid systems, both inside and outside of a containment. Protective measures to satisfy the postbreak criteria include either physical isolation, if possible, from postulated pipe rupture locations or the installation of massive pipe whip restraints and jet impingement shields. These restraints and shields, however, can limit access for in-service inspections, can increase the radiation exposure associated with in-service inspection and maintenance, and are expensive to design and install.

A typical PWR may have about 300 pipe whip restraints. The engineering effort required on the part of the architect-engineer to deal with the problem can consume as many as 250,000 man-hours, more than the time required for the entire balance-of-plant design work for some operating 500–600-MW nuclear plants. Estimated costs for the design and construction work that is associated with pipe break hardware for a typical unit are from $30 million to $50 million.

Experiments and analyses show that a double-ended guillotine break is unlikely and that a detectable leak would be expected well in advance of the crack growth that would result in such a break. This means that leaks can be detected and pipes can be repaired before a sudden rupture of a flawed pipe takes place. Therefore, most pipe whip restraints and jet impingement shields are probably unnecessary. There is consensus in the nuclear industry and recognition within the NRC staff that the exclusion of PWR primary-loop double-ended guillotine pipe ruptures from the design basis would be acceptable and that the scope of this exclusion may be extended to other high-energy piping, including the replacement of main coolant pipes in BWRs.

Pipe whip restraints and the structural framework supporting them can lead to various other problems. The congestion they create can make recovery from unusual plant conditions (e.g., radioactive release or spill) inside the plant more difficult. Also, access for fire control within these areas of the plant is limited, especially during low-visibility conditions. There is also a significant increase in heat loss to the containment. This effect is particularly pronounced with reflective metal insulation and is a major contributor to the tendency of many containments to operate at temperatures very near specified limits.

EPRI pioneered work on simplified methods for evaluating flawed ductile piping. This was applied and extended to the intergranular stress corrosion cracks found in BWR piping; the extensions included consideration of leak before break (LBB) in the BWR piping systems. Later, EPRI's work found direct application to consideration of LBB analyses in pipe whip and jet impingement shield exemptions. This later work is currently assigned a high priority.

The guideline study on applying LBB to reduce pipe whip restraints and jet impingement shields is nearing completion. It contains several cautions for the utilities. First, leak detection inside and outside a containment is a vital part of the LBB story. LBB should not be applied to socket-welded piping because this piping has a high failure rate. Nor is LBB applicable to ferritic piping when the line temperature is lower than 200°F (93°C) unless it can be shown that the material is on the upper shelf at the specified minimal operational temperature of interest for the LBB evaluation. The presence of cast materials and weldments requires special consideration, data, or discussion to demonstrate compliance with NRC's LBB acceptance criteria; for piping systems with positive displacement pumps or other vibration sources, it must be shown that fatigue cracking will not occur. Pipe diameters under 6 in may be more difficult to qualify.

EPRI's validated LBB methods package to justify removal of unnecessary hardware is available to member utilities. The EPRI package was transferred to Duquesne Light Co. for use by its contractor, R. L. Cloud Associates, Inc., for application at Beaver Valley, Unit 2. Experience with this application has strengthened the package for use by other EPRI member utilities. The package includes the computer codes PICEP and FLET. The package also contains an extensive materials data base that has been assembled for carbon steel and stainless steel base metal and weld metal.

Vendor-specific LBB reports for four vendors (Westinghouse Electric Corp., Combustion Engineering, Inc., Babcock & Wilcox Co., and General Electric Co.) have been completed. The studies provide a comparison of the approach selected by each vendor for applying LBB to high-energy piping and include guidelines to help the utilities determine the lines to which LBB can be applied to achieve the greatest overall benefit.

EPRI has also started several other tasks to provide maximum near-term benefits to the utility industry in its efforts to reduce the number of pipe whip restraints and jet impingement shields. The objectives are as follows.

- Develop guidelines, technical justifications, cost benefits, and criteria for reducing the number of pipe whip restraints and jet impingement shields
- Assess integrity concerns for centrifugally cast piping and statically cast fittings (toughness degradation, stress corrosion cracking, fatigue, inspectability)
- Assess the application of displacement versus load control for degraded piping to demonstrate additional margins for evaluation of flawed piping
- Continue effort on improving NDE technology for defining the minimum flaw that can be detected with high confidence
- Demonstrate and deliver the technology to the utilities

Three EPRI-sponsored tests at Wyle Laboratories to evaluate various leak detection methods have been successfully completed (Figure 1). The results of the evaluation show that

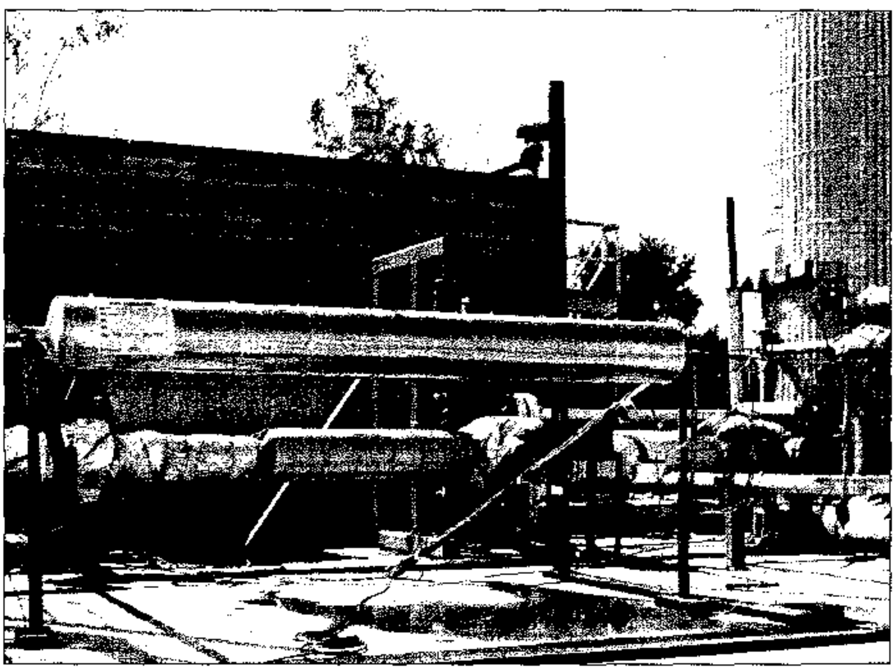


Figure 1 EPRI-sponsored test facility at Wyle Laboratories, Norco, California, for evaluating the effectiveness of various leak detection methods outside containment.

visual inspection is a very effective way to discover leaks. Insulation is permeable to steam and water flow, and the aluminum canister around the pipe insulation deforms as a result of the leak. Steam and water leaks are clearly visible down to the lowest flow rates tested—approximately 0.1 gal/min. Three types of insulation (calcium silicate, reflective fiberglass, and encapsulated fiberglass) were evaluated in the tests. This work should help all utilities apply the leak-before-break concept to high-energy piping that is outside of containment.

Many of the projects started after the piping integrity matrix was established in April 1985 are nearing completion, and results from some of the preliminary reports are already in use at several utilities. Fifteen reports pertaining to matrix activities will be published shortly. A workshop, attended by representatives from 38 utilities, was held October 7–8, 1986 to transfer this technology. *Project Managers: Bindi Chexal, Douglas Norris, and Hui-tsung Tang*

FRACTURE PROPERTIES OF NODULAR CAST-IRON CASKS

The demand for containers that can be used to dry-store and transport spent nuclear fuel from LWRs in the United States will increase considerably over the next several years; the principal users are electric utilities and government agencies. Spent fuel is usually stored in water pools at reactor sites. With the enactment of the Nuclear Waste Policy Act in 1982, DOE assumed responsibility for the ultimate disposal of fuel in the United States, but utilities are responsible for on-site storage. To increase storage capacity at reactor sites, at least three technically feasible alternatives are available to electric utilities: spent-fuel pool reracking, fuel consolidation, and on-site temporary dry storage.

One class of design for the dry storage of fuel comprises large metal casks that would also have the potential for use as shipping casks for transporting spent fuel off-site. These containers are massive because their design must provide for radiation shielding, nuclear criticality, heat loading, leak tightness, and mechanical and impact load considerations. Current casks are fabricated from stainless steel with lead shielding. Monolithic ferritic casks can also be designed to meet these objectives and have the potential to effect important cost savings in comparison with other designs.

When safety requirements and cost considerations are taken into account, a ductile iron casting is an attractive option for the storage or transport of spent fuel. A typical design requires a cask of about 100 t to ship 10 t of spent fuel. A key issue associated with the use of nodular iron for the transportation of spent-fuel casks is the fracture behavior under transportation accident impact loads. For example, the Code of Federal Regulations requires that the cask withstand a hypothetical accident in which it is dropped from a 30-ft height onto an essentially unyielding surface while the cask temperature is −20°F (−29°C). These cask safety specifications can be met by reducing the stress levels that can result from the postulated accidents (e.g., using removable impact limiters) and by selecting materials that have adequate fracture toughness.

Although casks are fabricated to extremely stringent quality assurance and inspection standards, further conservatism in design is obtained by assuming the presence of a sharp, undetected flaw in the cask body material. When this sharp flaw or defect in a material is subjected to an applied tensile stress, stresses are intensified at the tip of the flaw as these surfaces pull away from one another. The material should be capable of resisting these forces, thereby preventing crack initiation and growth. The extent to which a material resists the pull-away forces determines its fracture toughness. Before applying fracture mechanics analyses to a spent-fuel cask, the expected response of the cask body to the hypothetical drop is calculated. Then the analyses are used to determine the location and magnitude of the maximum stresses that develop at impact, and a flaw is assumed to exist at that site. The size of the flaw is conservatively assumed to be greater than that which can be detected with nondestructive inspection techniques. The combination of stresses and the assumed flaw defines the applied stress intensity. Analyses and tests are conducted to ensure an adequate margin with respect to crack initiation.

In a recent EPRI project, Sandia National Laboratories and Fracture Control Corp. obtained fracture toughness data on a variety of ductile iron materials. The data show that good fracture toughness properties can be achieved through control of material chemistry, pearlite content, and graphite nodule shape and distribution.

These results are important because they can be used to define a procurement specification for the material that ensures its suitability for application to spent-fuel storage and transportation casks. ASTM is now preparing a standard specification based on the results of this and other related EPRI projects. The overall objective of this EPRI work is to develop technical support for the licensing and use of competitive cask materials and high-payload cask designs. *Project Managers: Joseph Santucci and R. F. Williams*

New Contracts

Project	Funding/ Duration	Contractor/EPRI Project Manager
Advanced Power Systems		
Dynamic Operating Benefits: Measurement and Applications (RP1084-24)	$149,000 9 months	Decision Focus, Inc./ *T. Yau*
Development of Point-Contact Cell Mount (RP1415-11)	$94,800 9 months	Acrian, Inc./*J. Cummings*
Coal Combustion Systems		
Fossil Fuel Plant Retrofits for Improved Heat Rate and Availability (RP1403-16)	$54,500 6 months	Gilbert/Commonwealth, Inc./*G. Touchton*
Leaning Brick Stack Liners (RP1871-18)	$268,700 25 months	Battelle Memorial Institute/*R. Moser*
Electrical Systems		
Feasibility of Advanced Package for Thyristors (RP2443-8)	$273,600 28 months	General Electric Co./ *H. Mehta*
Advanced Power Transformer (RP2618-2)	$1,521,400 17 months	Westinghouse Electric Corp./*D. Sharma*
Woodpecker Repellent Studies (RP2835-1)	$84,300 15 months	Southwest Research Institute/*J. Dunlap*
Castable Substation Insulators (RP2841-1)	$280,000 21 months	Battelle Memorial Institute/*J. Dunlap*
Technical Limitations to Transmission System Operations (RP5005-2)	$180,300 12 months	Power Technologies, Inc./ *J. Mitsche, F. Young*
Oxidation Phenomena in Water Treeing (RP8000-3)	$221,100 12 months	Hydro-Québec Research Institute/*B. Bernstein*
Energy Management and Utilization		
Residential Energy Use Comparison Project (RP2342-7)	$50,000 10 months	Quantum Consulting, Inc./ *S. Braithwait*
Electrochemical Process Assessment (RP2416-27)	$51,700 9 months	Prototech Co./*L. Harry*
Design of Industrial Process Refrigeration Systems (RP2783-4)	$191,000 7 months	Union Carbide Corp./ *A. Karp*
Development of a House Electrical Load Simulator for EPRI Load Control Emulator (RP2830-3)	$52,100 14 months	Meta Systems, Inc./ *L. Carmichael*
Dielectric Drying of Industrial Materials (RP2893-1)	$492,300 18 months	University of Texas at Austin/*A. Karp*
Electrochemical Measurement of Corrosion Rates (RP8002-9)	$200,000 25 months	SRI International/*B. Syrett*
Causes of Boiling Heat Transfer Degradation in Binary Mixtures (RP8006-2)	$75,000 20 months	National Bureau of Standards/*J. Kim*

Project	Funding/ Duration	Contractor/EPRI Project Manager
Nuclear Power		
Plugging Margin Criteria for Roll Transitions (RPS301-9)	$185,800 8 months	Westinghouse Electric Corp./*L. Williams*
Point Beach-1 Tubesheet Crevice Chemistry and Sludge Composition (RPS304-19)	$135,000 6 months	Battelle, Columbus Laboratories/*P. Paine*
GUST Code Improvement and Documentation (RPS309-5)	$31,700 4 months	Jaycor/*G. Srikantiah*
EPRI/PHDR Seismic Experiments Using a Large Shaker (RP1444-8)	$101,100 5 months	Kernforschungszentrum Karlsruhe GmbH/*A. Singh*
Analysis of Large-Scale Seismic Experiment in Lotung, Taiwan (RP2225-9)	$206,500 15 months	Bechtel Group, Inc./ *Y. Tang*
Analysis of Large-Scale Seismic Experiment in Lotung (RP2225-14)	$78,600 16 months	Sargent & Lundy/*Y. Tang*
Analysis of Large-Scale Seismic Experiment in Lotung (RP2225-15)	$96,800 14 months	Impell Corp./*Y. Tang*
Piping Vibration From Two-Phase Steam-Water Flow (RP2290-7)	$40,500 32 months	Ontario Hydro/*J. Kim*
Research Reactor Loop Water Chemistry Studies (RP2295-4)	$1,245,800 46 months	Massachusetts Institute of Technology/*C. Wood*
Development and Demonstration of Plant Waste Volume Minimization Program (RP2414-8)	$50,000 16 months	Analytical Resources, Inc./*P. Robinson*
BWR Radiation Field Assessment (RP2494-1)	$307,000 44 months	General Electric Co./ *C. Wood*
Piping System Damping Evaluation (RP2635-2)	$99,700 9 months	Bechtel Group, Inc./ *H. Tang*
Preliminary Conceptual Design Study for a Small LWR (RP2660-8)	$304,700 13 months	General Electric Co./ *W. Sugnet*
Advanced LWR Program: Requirements Document (RP2660-9)	$1,000,000 54 months	Stone & Webster Engineering Corp./*J. DeVine*
Supporting Research for Advanced LWR Requirements Document and Small Plant Conceptual Designs (RP2660-10)	$998,000 57 months	Massachusetts Institute of Technology/*W. Sugnet*
In-core Electrochemical Potential and Irradiation-Assisted Stress Corrosion Cracking (RP2680-5)	$98,300 13 months	General Electric Co./ *S. Gehl*
Component Monitoring and Diagnostics Technology Transfer (RP2720-1)	$955,600 48 months	Advanced Technology Engineering Systems, Inc./*G. Shugars*
Hydrogen Diffusion From Radwaste Packages (RP2724-2)	$74,800 10 months	Science Applications International Corp./ *P. Robinson*
Qualification of PWR Steam Generator Chemical Cleaning at Indian Point-2 (RP2755-11)	$866,600 19 months	Westinghouse Electric Corp./*L. Williams*

New Technical Reports

Requests for copies of reports should be directed to Research Reports Center, P.O. Box 50490, Palo Alto, California 94303; (415) 965-4081. There is no charge for reports requested by EPRI member utilities, U.S. universities, or government agencies. Others in the United States, Mexico, and Canada pay the listed price. Overseas price is double the listed price. Research Reports Center will send a catalog of EPRI reports on request. For information on how to order one-page summaries of reports, contact the EPRI Technical Information Division, P.O. Box 10412, Palo Alto, California 94303; (415) 855-2411.

ADVANCED POWER SYSTEMS

Photovoltaic Manufacturing Cost Analysis: A Required-Price Approach
AP-4369 Final Report (RP1975-1); Vol. 1, $32.50; Vol. 2, $47.50
Contractor: Research Triangle Institute
EPRI Project Managers: R. Taylor, E. DeMeo

Inspection and Performance Evaluation of Dams: A Guide for Managers, Engineers, and Operators
AP-4714 Final Report (RP1745-14); $40
Contractor: Morrison-Knudsen Engineers, Inc.
EPRI Project Manager: C. Sullivan

Roller-Compacted Concrete for Dams
AP-4715 Interim Report (RP1745-16); $40
Contractor: Morrison-Knudsen Engineers, Inc.
EPRI Project Manager: C. Sullivan

Summary Report: Rotary Separator–Turbine
AP-4718 Final Report (RP1196); $25
Contractors: Transamerica Delaval/Biphase Energy Systems; Utah Power & Light Co.
EPRI Project Manager: E. Hughes

Cavitation Pitting Mitigation in Hydraulic Turbines
AP-4719 Final Report (RP1745-10); Vol. 1, $32.50; Vol. 2, $40
Contractor: Acres International Corp.
EPRI Project Managers: J. Birk, A. Ferreira

Thermoeconomic Analysis of a Gasification–Combined-Cycle Power Plant
AP-4734 Final Report (RP2029-8); $32.50
Contractor: Desert Research Institute
EPRI Project Manager: M. Gluckman

High-Concentration Photovoltaic Module Design
AP-4752 Interim Report (RP1415-7); $47.50
Contractor: Black & Veatch Engineers-Architects
EPRI Project Managers: J. Cummings, R. Taylor

Products of Two-Stage Liquefaction as Combustion Turbine Fuels
AP-4761 Final Report (RP2112-5); $32.50
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: W. Rovesti

Demonstration Test of a 500-kW Peak-Shaving Lead-Acid Battery Energy Storage System
AP-4841 Final Report (RP255-2, -9); $25
Contractor: Public Service Electric & Gas Co.
EPRI Project Manager: W. Spindler

COAL COMBUSTION SYSTEMS

Integrated Environmental Control: Application of Design Strategy
CS-4439 Final Report (RP1609-1); Vol. 2, $47.50
Contractor: Stearns Catalytic Corp.
EPRI Project Manager: E. Cichanowicz

Solid-Particle Erosion of Utility Steam Turbines: 1985 Workshop
CS-4683 Proceedings (RP1885-5); $255
Contractor: Delian Corp.
EPRI Project Manager: T. McCloskey

Investigation of Precipitator Pulse Energization
CS-4717 Final Report (RP1868-1); $300
Contractor: Southern Research Institute
EPRI Project Manager: W. Piulle

Proceedings: 1985 Fossil [Fuel] Plant Cycling Workshop
CS-4723 Proceedings (RP1184-18); $70
Contractor: Encor-America, Inc.
EPRI Project Manager: R. Leyse

Proceedings: 1985 Heat Rate Improvement Workshop
CS-4736 Proceedings (RP1711-3); $62.50
Contractor: Encor-America, Inc.
EPRI Project Manager: R. Leyse

Nondestructive Inspection Systems for Boiler Tubes
CS-4742 Final Report (RP1865-1); $40
Contractor: Aptech Engineering Services, Inc.
EPRI Project Manager: J. Scheibel

Proceedings: Second EPRI Incipient-Failure-Detection Conference
CS-4748 Proceedings (RP1864-2); $77.50
Contractor: Radian Corp.
EPRI Project Manager: J. Scheibel

High-Volume Fly Ash Utilization Program Guidelines
CS-4763 Final Report (RP2422-2); $25
Contractor: GAI Consultants, Inc.
EPRI Project Manager: D. Golden

Transportation Cost Estimates for Sodium Compounds
CS-4764 Final Report (RP1682-4); $25
Contractor: University of Tennessee
EPRI Project Manager: R. Hooper

Evaluation of Plastic Filler Applications for Leached Fly Ash
CS-4765 Final Report (RP2422-11); $32.50
Contractor: Ontario Research Foundation
EPRI Project Manager: D. Golden

ELECTRICAL SYSTEMS

Improved Motors for Utility Applications: Impact of Harmonics
EL-4286 Final Report (RP1763-2); Vol. 4, $32.50
Contractor: General Electric Co.
EPRI Project Manager: D. Sharma

Decision Theory Approach to Identifying Bad Data in State Estimation for Power Systems
EL-4325 Final Report (RP1999-6); $25
Contractor: University of California at Berkeley
EPRI Project Managers: M. Pereira, C. Frank

500-kV HVDC Air-Blast Circuit Breaker
EL-4520 Final Report (RP1507-3); $32.50
Contractor: BBC Brown Boveri, Inc.
EPRI Project Manager: J. Porter

Concurrent Processors for Computation of Power System Reliability: Phase 1
EL-4598 Final Report (RP2473-5); $25
Contractor: Northwestern University
EPRI Project Managers: R. Iveson, M. Pereira

Reliability Models of Interconnected Systems That Incorporate Operating Considerations
EL-4603 Final Report (RP1534-2); Vol. 1, $32.50
EL-4603-CCM Computer Code Manual; Vol. 2, $32.50
Contractor: Associated Power Analysts, Inc.
EPRI Project Manager: N. Balu

Structural Development Studies at the EPRI Transmission Line Mechanical Research Facility
EL-4756 Interim Report (RP2016-3); $32.50
Contractor: Sverdrup Technology, Inc.
EPRI Project Manager: P. Lyons

Development of a Computer Program for Fast Estimation of Voltages
EL-4798 Final Report (RP2148-3); Vol. 1, $32.50; Vol. 2, $32.50
Contractor: Carlsen & Fink Associates, Inc.
EPRI Project Manager: J. Mitsche

ENERGY MANAGEMENT AND UTILIZATION

Small-Hydropower Development: The Process, Pitfalls, and Experience—Guide for Developers
EM-4036 Final Report (RP1745-15); Vol. 4, $40
Contractor: Morrison-Knudsen Engineers, Inc.
EPRI Project Manager: C. Sullivan

Assessment of Hybrid Electric Propulsion Systems for Motor Vehicles
EM-4700 Final Report (RP1136-28); $25
Contractor: Roy A. Renner
EPRI Project Manager: L. O'Connell

EPRI and TVA Testing and Evaluation of Electric Work Vehicles

EM-4702 Final Report (RP1136-17); $32.50
Contractor: Tennessee Valley Authority
EPRI Project Manager: L. O'Connell

Forecasting Electricity Sales Over the Short Term: A Comparison of New Methodologies

EM-4772 Final Report (RP2279-2); $32.50
Contractors: Quantitative Economic Research, Inc.; Scientific Systems, Inc.
EPRI Project Manager: A. Faruqui

Impact of Rate Structure on Demand-Side Management Programs

EM-4791 Interim Report (RP2440-1); Vol. 1, $25; Vol. 2, $32.50
Contractors: National Economic Research Associates, Inc.; Minimax Research Corp.
EPRI Project Managers: W. Smith, J. Chamberlin

Survey of Utility Industrial Demand-Side Management Programs

EM-4800 Final Report (RP2613-2); $32.50
Contractor: Synergic Resources Corp.
EPRI Project Managers: C. Gellings, L. Harry

ENVIRONMENT

Proceedings: Methods for Acidic Deposition Measurement

EA-4663 Proceedings (RP1630-52); $40
Contractor: Envirotest
EPRI Project Manager: P. Mueller

Multiple Perspectives: Bridging the Gap Between Analysis and Action

EA-4669 Final Report (RP2379-13); $25
Contractor: Systems Forecasting, Inc.
EPRI Project Manager: D. Geraghty

Reserves and Potential Supply of Low-Sulfur Appalachian Coal

EA-4710 Final Report (RP2369-30); $32.50
Contractor: Charles River Associates, Inc.
EPRI Project Manager: J. Platt

Techniques for Chemical Analysis of Radionuclides in Fly Ash: An Evaluation

EA-4728 Final Report (RP1620-8); $25
Contractor: Battelle, Pacific Northwest Laboratories
EPRI Project Manager: J. Guertin

Mobilization and Attenuation of Trace Elements in an Artificially Weathered Fly Ash

EA-4747 Final Report (RP2485-1); $32.50
Contractor: University of Alberta
EPRI Project Manager: I. Murarka

Utility Fuel Inventory Model: Version 2.0

EA-4766-CCM Computer Code Manual (RP2314); $47.50
Contractors: Applied Decision Analysis, Inc.; Decision Focus, Inc.
EPRI Project Managers: H. Chao, S. Chapel, S. Wan

Forest Health and Acidic Deposition

EA-4813-SR Special Report (RP5002); $25
EPRI Project Managers: C. Hakkarinen, M. Allan

Proceedings: 1985 Fuel Supply Seminar

EA-4857 Proceedings (RP2369-10); $47.50
Contractor: Atlantis, Inc.
EPRI Project Manager: J. Platt

NUCLEAR POWER

A Full-Range Drift-Flux Correlation for Vertical Flows (Revision 1)

NP-3989-SR (Rev. 1) Special Report; $25
EPRI Project Managers: B. Chexal, G. Lellouche

FLECHT SEASET Program: Final Report

NP-4112 Final Report (RP959-1); $47.50
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: A. Singh

The Reactor Analysis Support Package (RASP): PWR Set-Point Methodology

NP-4498 Final Report (RP1761-12); Vol. 7, $32.50
Contractor: SMT Associates
EPRI Project Manager: L. Agee

Comparisons of COBRA–SFS Calculations With Data From Simulated Sections of Unconsolidated and Consolidated BWR Spent Fuel

NP-4593 Final Report (RP2406-2); $25
Contractor: Battelle, Pacific Northwest Laboratories
EPRI Project Manager: R. Lambert

Application of Environmental Fatigue Stress Rules to Carbon Steel Reactor Piping

NP-4644M Final Report (RP1543-8); Vol. 1, $25; Vol. 2, $25
Contractor: General Electric Co.
EPRI Project Manager: R. Jones

Relationship Between Turbine Rotor and Disk Metallurgical Characteristics and Stress Corrosion Cracking Behavior

NP-4695M Final Report (RP1929-6); $25
Contractor: Transamerica Delaval, Inc.
EPRI Project Manager: R. Jones

Seismic Hazard Methodology for the Central and Eastern United States

NP-4726 Final Report (RP101-38, -45, -46; RP2556-14); Vol. 1, $40
Contractors: Risk Engineering, Inc.; Woodward-Clyde Consultants; Geomatrix Consultants, Inc.; Cygna Corp.
EPRI Project Managers: C. Stepp, J. King

Side-by-Side Comparison of Techniques for Analyzing Organic Acids, Total Organic Carbon, and Anions

NP-4731 Final Report (RPS306-12, -13); $32.50
Contractors: Westinghouse Electric Corp.; NWT Corp.
EPRI Project Manager: S. Hobart

Proceedings: 1985 Nuclear Power Plant Safety Control Technology Seminar

NP-4750-SR Proceedings; $70
EPRI Project Managers: M. Divakaruni; B. Sun

CALENDAR

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

JANUARY

20–21
Seminar: Maintaining Equipment Qualification
New Orleans, Louisiana
Contact: Robert Kubik (415) 855-8905

21–22
Seminar: Maintaining Equipment Qualification
Washington, D.C.
Contact: Robert Kubik (415) 855-8905

22–23
Seminar: Maintaining Equipment Qualification
Washington, D.C.
Contact: Robert Kubik (415) 855-8905

FEBRUARY

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

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

MARCH

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

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

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

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

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

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