The Rush to Superconductivity

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Cover: The phenomenon of superconductivity is thought to involve the movement of electrons in Cooper pairs through specific planes of a material's crystal lattice. The orderly flow of the paired electrons eliminates all electrical resistance in the conductor.

Superconductivity: Preparing for the Possibilities

Recent development of ceramic materials that become superconducting at liquid nitrogen temperatures has created considerable excitement in the scientific community, but what is this discovery apt to mean for the electric power industry?

Some possible applications of the new materials appear obvious, as do their limitations, on the basis of our still evolving understanding of their properties. The efficiency of underground transmission lines and generators could be improved, for example. But these systems are already very efficient, and the new materials would not offer major breakthroughs in performance. Nevertheless, if technical hurdles in materials design and fabrication can be overcome, these uses could become economically viable in the future. Superconducting magnets could be used to store electric energy directly, offering perhaps the most significant potential for the new class of superconductors. They could also accelerate development of fusion energy and magnetohydrodynamics, although these technologies face other, more serious technical and economic barriers.

The challenges are formidable, but we shouldn't let such clearly foreseen obstacles dishearten us. As with so many scientific breakthroughs in the past, the really revolutionary effect of these new materials may come in ways not yet anticipated, particularly if room-temperature superconductors are eventually developed. The most important contribution of the recent flurry of research may turn out to be in improved *theories* of superconductivity. Theoretical understanding of the phenomenon could really open the door, taking us beyond cut-and-try research to true scientific engineering of higher-temperature superconductor materials that are inherently easier to fabricate. That's what excites me and why I have urged our staff to anticipate further breakthroughs when assessing opportunities for application.

Whatever the theory and experiments place before us, long-term, coordinated research will be needed before this technology becomes widely integrated into utility systems. EPRI is now working with other funding agencies to develop a coordinated R&D plan that will keep all parties up-to-date on both the basic research and the opportunities for practical application. In this way, we are positioning ourselves to take advantage of the scientific breakthroughs as they come—creating an indirect pull on basic research, as well as a direct push on technology development.

I believe the breakthroughs will come sooner than many have predicted. We can envision great improvements in the generation, storage, and delivery of electricity, but the imagination really soars with the possibilities for end use. As microminiaturized electronic circuits did in past decades, high-temperature superconductors could offer products and processes as yet unconceived. Integration of such innovations into the mainstream of society carries the potential for profound economic change as well as lasting practical improvements in the way we live.

Richard E. Balzhiser
Executive Vice President

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RESEARCH UPDATE

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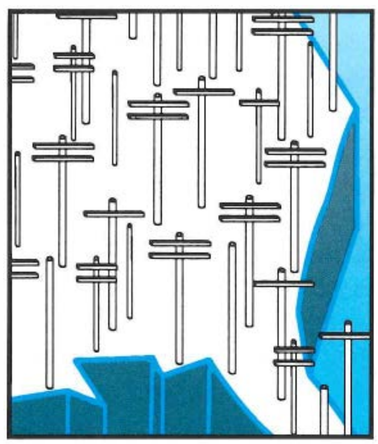

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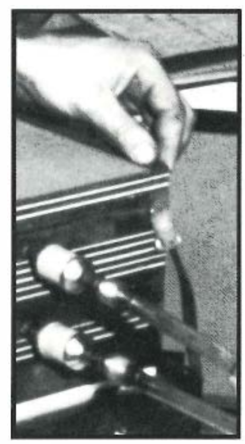

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DEPARTMENTS

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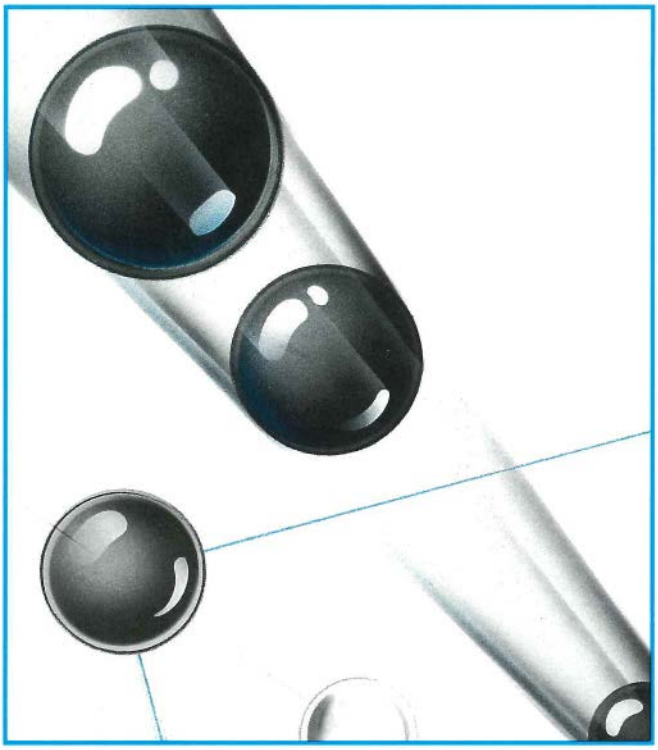
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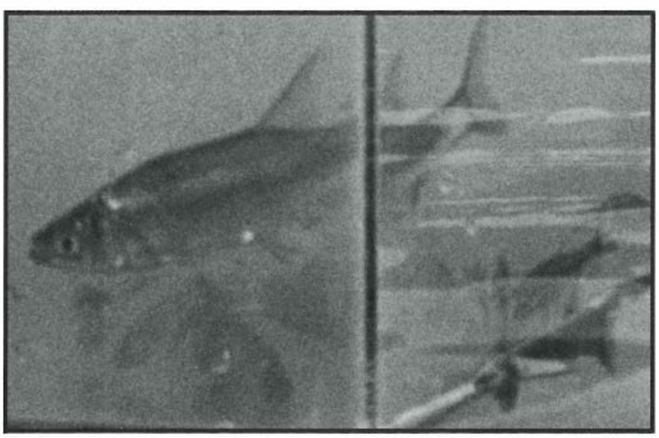
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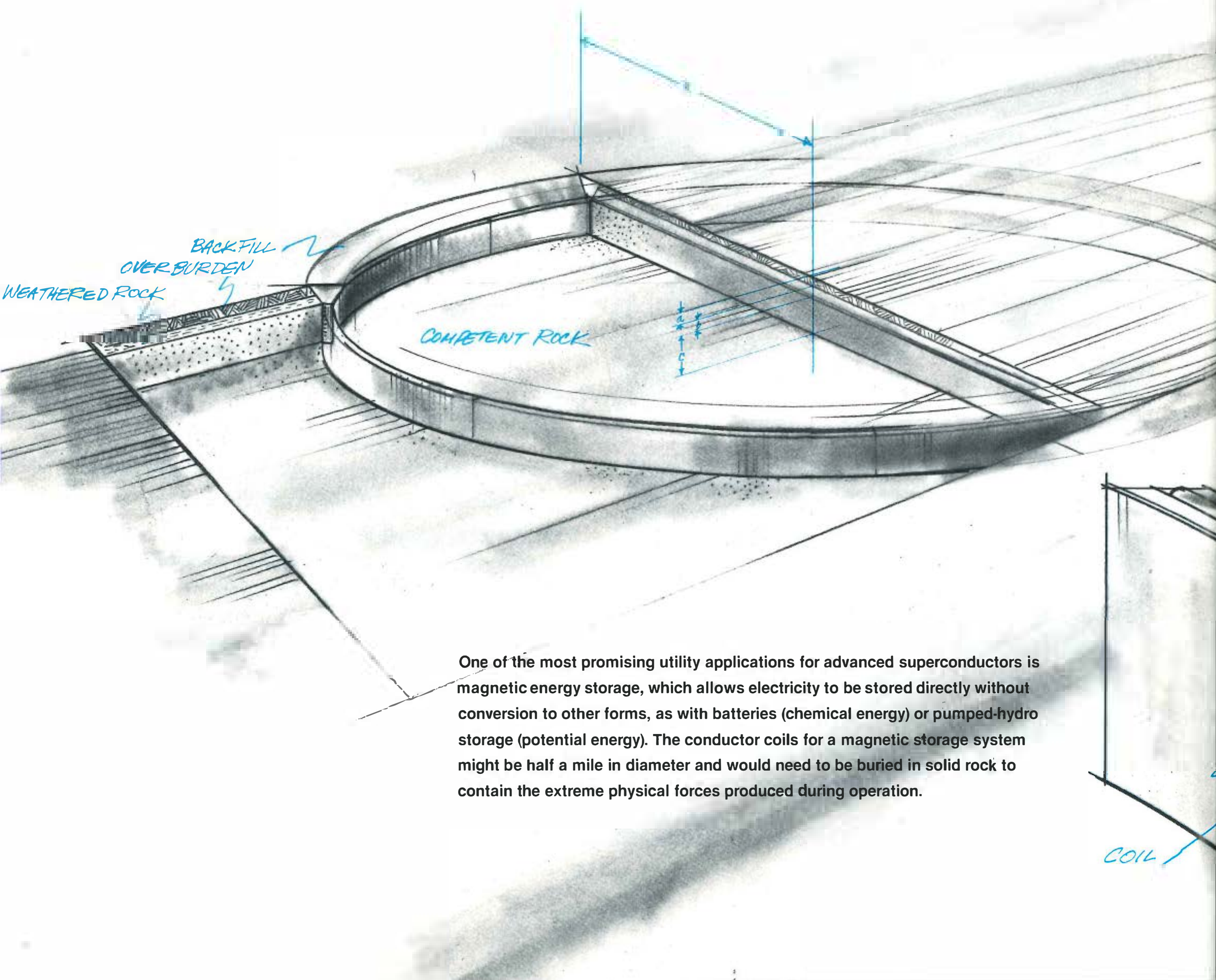
PURSUING THE PROMISE O

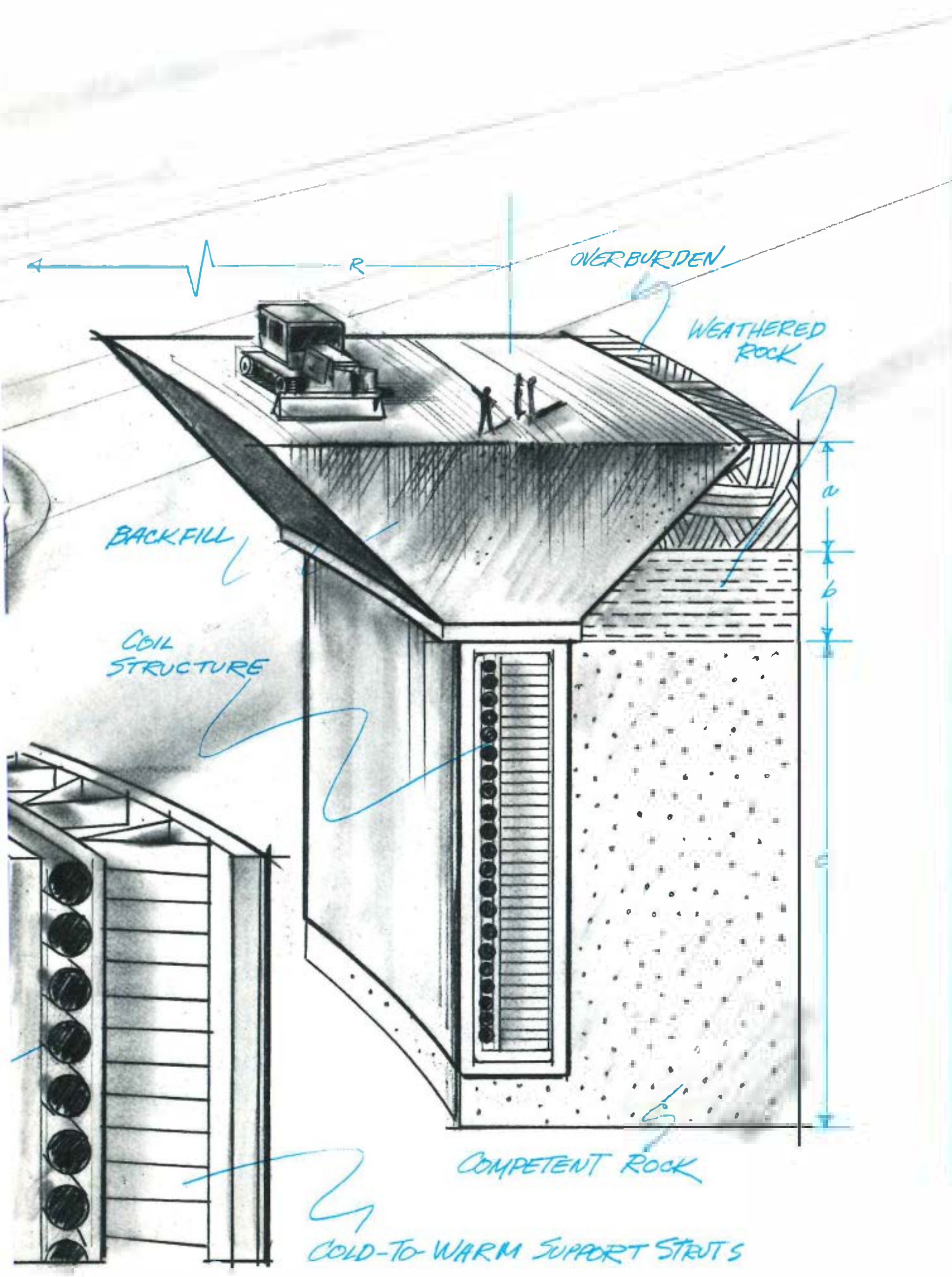
Experiments are outpacing theory as new achievements in high-temperature superconductivity follow one
superconductors will have an enormous impact on how we create and use electricity.



One of the most promising utility applications for advanced superconductors is magnetic energy storage, which allows electricity to be stored directly without conversion to other forms, as with batteries (chemical energy) or pumped-hydro storage (potential energy). The conductor coils for a magnetic storage system might be half a mile in diameter and would need to be buried in solid rock to contain the extreme physical forces produced during operation.

F SUPERCONDUCTIVITY

nother in rapid succession. If basic technical barriers can be overcome,



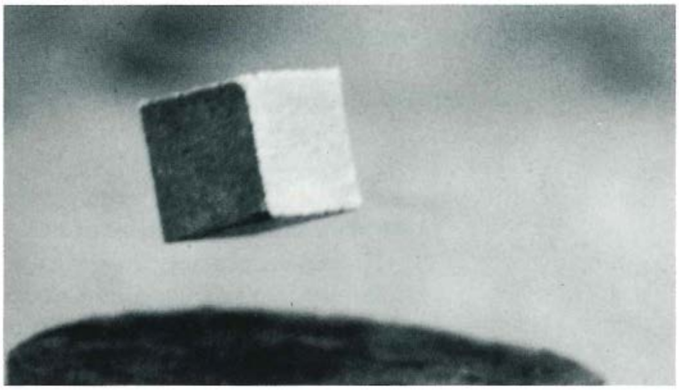
The discovery of so-called hot superconductors has created a unique challenge for the electric power industry. Not since the days of Thomas Edison has a new technology promised such opportunities for fundamental change or raised such puzzling questions about how to fulfill this promise.

Superconductors carry electricity with virtually no losses and can produce powerful magnetic fields with expenditure of little energy. Until recently, these properties could be maintained only by immersing superconducting metal alloys in relatively expensive, difficult-to-handle liquid helium. Now a new class of ceramic materials has been found that becomes superconducting at temperatures sustainable by liquid nitrogen at about one twenty-fifth the cost of liquid helium. Even at such higher temperatures, however, practical applications of superconductivity may remain limited by a variety of technical and economic factors.

Uncertainties abound: Will these new materials be able to carry large enough currents for them to be useful in high-power applications? Can ways be found to fabricate the brittle ceramics into flexible wires or other shapes that can become integral parts of rugged electric and magnetic machinery? Are room-

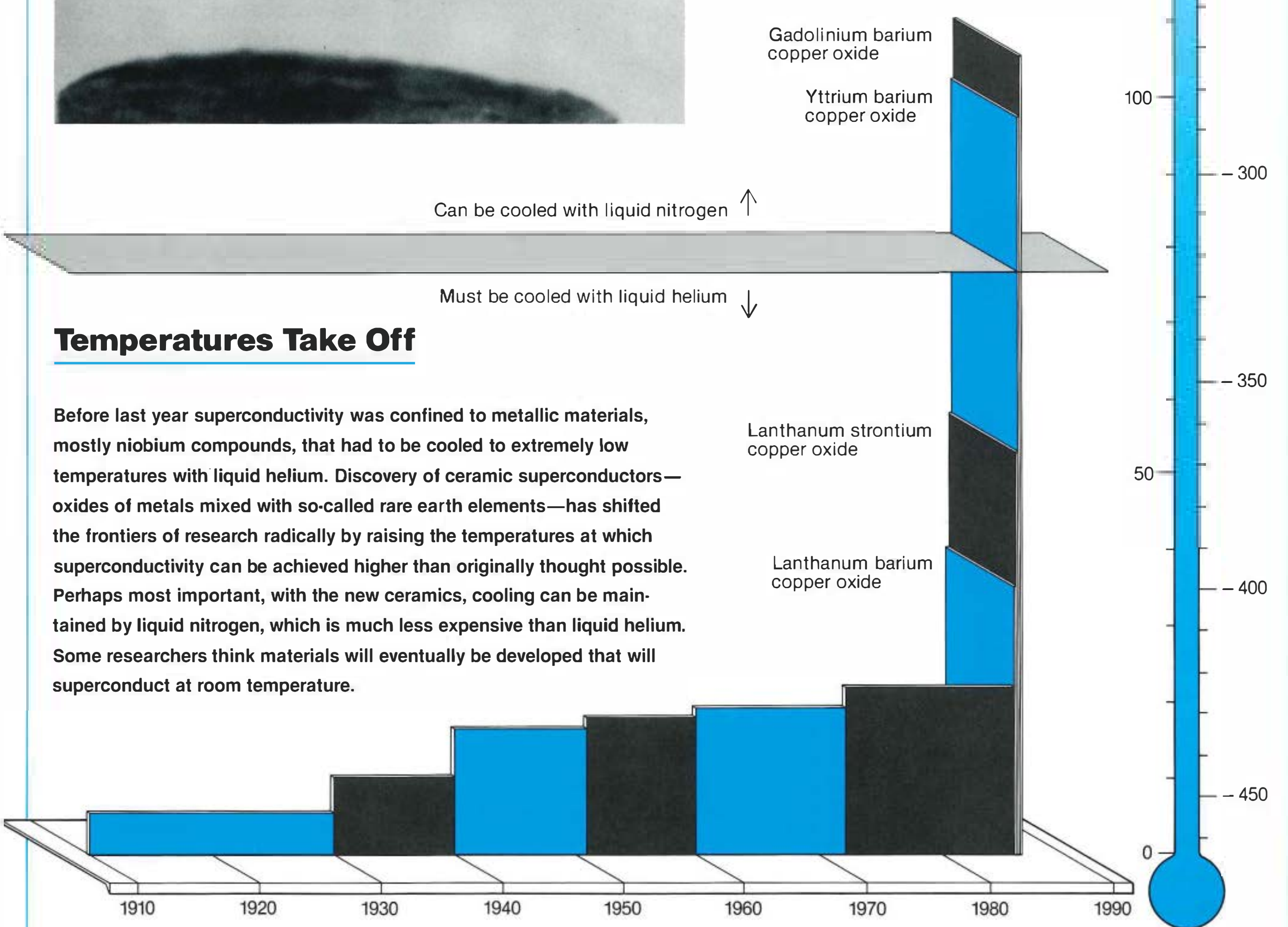
Testing for Superconductivity

Besides conducting electricity without loss, superconductors also have unique magnetic properties that can be used to test for their presence. Here, a permanent magnet floats above a superconductor bathed in liquid nitrogen because its magnetic field is completely repulsed at the surface of the superconductor—a phenomenon known as the Meissner effect.



Temperatures Take Off

Before last year superconductivity was confined to metallic materials, mostly niobium compounds, that had to be cooled to extremely low temperatures with liquid helium. Discovery of ceramic superconductors—oxides of metals mixed with so-called rare earth elements—has shifted the frontiers of research radically by raising the temperatures at which superconductivity can be achieved higher than originally thought possible. Perhaps most important, with the new ceramics, cooling can be maintained by liquid nitrogen, which is much less expensive than liquid helium. Some researchers think materials will eventually be developed that will superconduct at room temperature.



temperature superconductors—needing no expensive refrigeration to maintain their electrical properties—just around the corner, or are they only a pipe dream?

"To me, the excitement of recent developments comes from the possibility of doing things we haven't been able to do before," says Richard Balzhiser, EPRI's executive vice president. "Basic research on these new materials is already going on in many parts of the world. EPRI's role will be to mine that research, to look for what's enabling about this new technology."

Thinking long-term

As the quest for high-temperature superconductors and an adequate theory to explain their behavior continues (box, p. 12), engineers are beginning to assess the technology opportunities they present. Already one fundamental conclusion seems clear. Several years, perhaps decades, will be needed for these new materials to have a significant effect on electric utility operations.

"Utility systems are already very efficient," says J C. White, program manager for plant electrical systems and equipment. "Conventional generators, for example, convert mechanical energy to electric energy with better than 98% efficiency. Adding superconductors might increase that efficiency by 0.5 to 1%. We'll have to look very carefully at the costs of building, cooling, and maintaining a superconducting generator with the new materials before deciding whether that extra 1% is worth the effort."

Such a detailed analysis has already been conducted for a superconducting generator that would use helium-cooled metal alloys. During the early 1980s, EPRI and Westinghouse Electric completed the design and manufacturing development work on a 300-megavolt-ampere (270-MW) superconducting generator. Plans to build the device were dropped, however, as utility orders for new generating plants continued to decline. A few experimental superconducting generators have been constructed on a much smaller scale.

Experience gained during this project illustrates the difficulties of adapting superconductor technology for large utility equipment—even if specific technical problems with the new ceramics, such as their brittleness, can be overcome. A superconducting generator would be somewhat more complex than conventional models, for example, because of the need to bathe its rotor in a refrigerated cooling fluid. The rotor design involves concentric cylinders insulated from each other by a vacuum space. Interior parts of the rotor would be subjected to extreme mechanical stresses but would be very difficult to reach for inspection or repair. The switch from liquid helium to liquid nitrogen might have little effect on the economic feasibility of such a generator because coolant and refrigeration costs represent only a small fraction of overall costs.

Nevertheless, superconducting generators appear to have several inherent advantages that might well justify the extensive development effort needed to perfect them. Given adequate current-carrying capacity, for example, they could be much smaller than conventional generators—perhaps only one half the size—and thus potentially be less expensive to manufacture and transport. The extra electricity generated because of a 1% gain in efficiency would probably provide enough revenue over the life of a superconducting generator to more than repay its total capital cost. Also, because of their longer response time to power surges on a line and their very high magnetic flux levels, such generators could enhance the stability of utility networks and thus perhaps reduce needed reserve margins.

"We have to think long term," says Frank Young, associate director of EPRI's Electrical Systems Division and chairman of the Superconductivity Interdivisional Coordinating Committee. "These new superconductors aren't going to be a panacea, certainly not any time soon for electric utilities. Ours is perhaps the most capital-intensive of all industries, with huge pieces of equipment and a primary concern for reliability. We not only have to evaluate which applications are most promising and solve numerous technical problems to develop them but we must also show that they can be built economically on a large scale and then operated reliably for decades."

ALTHOUGH the earliest uses of new superconducting materials are likely to occur outside the electric power industry in relatively small-scale, specialized applications, utilities may still benefit indirectly.

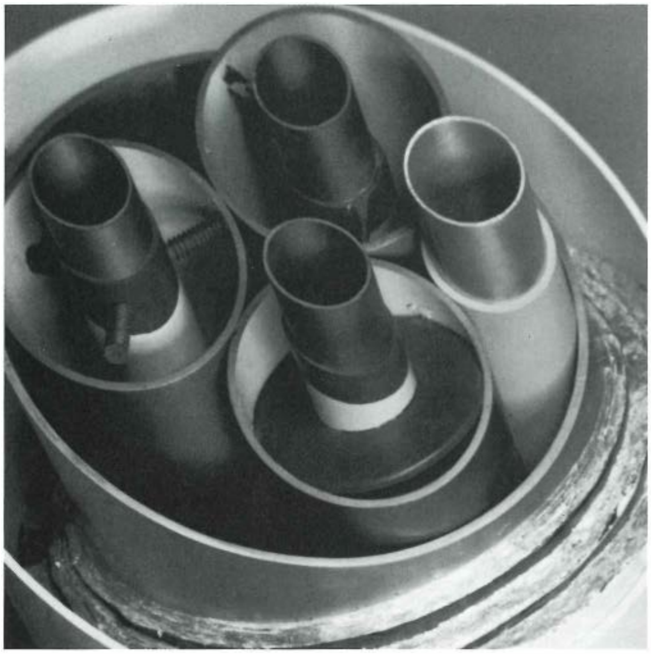
Superconducting switches called Josephson junctions, for example, can process information about 10 times faster than the circuits in conventional silicon chips. Adoption of Josephson junction technology to make faster computers could therefore significantly affect utility operations because the electric power industry is the third largest user of computers, trailing only the government and the banking industry.

Already some progress has been reported in fashioning the new ceramic superconductors into thin films that might be used in Josephson junction circuits, but again past experience with helium-cooled superconducting alloys raises a note of caution. Among other problems, repeated cooling and warming was found to damage Josephson junctions, and a competing technol-

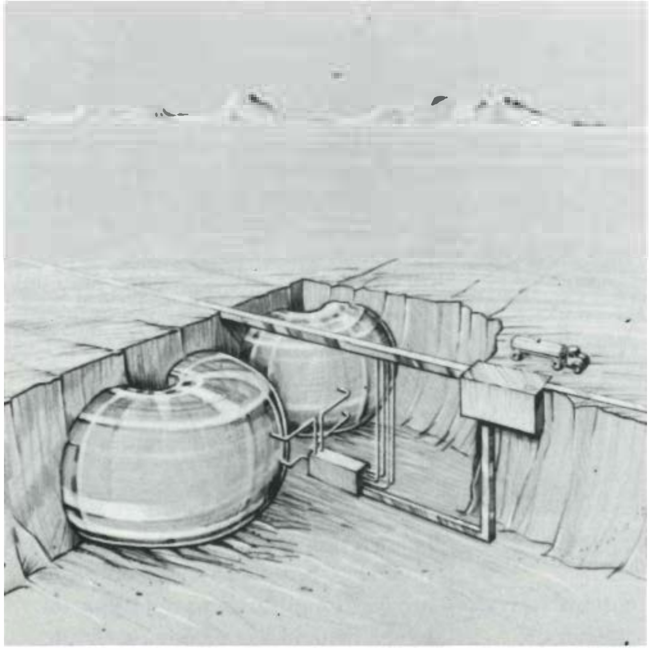
Utility Applications

The first large-scale utility application of superconductivity will probably come in underground transmission lines with extremely low losses, although the current-carrying capacity of the new materials will have to be increased first. Further in the future, superconducting magnets could open the door for direct storage of electricity, while using superconducting materials in generators could reduce their size and increase their efficiency. Long lead times will be needed for such potential applications to be proved and scaled up to the size required for utility operations.

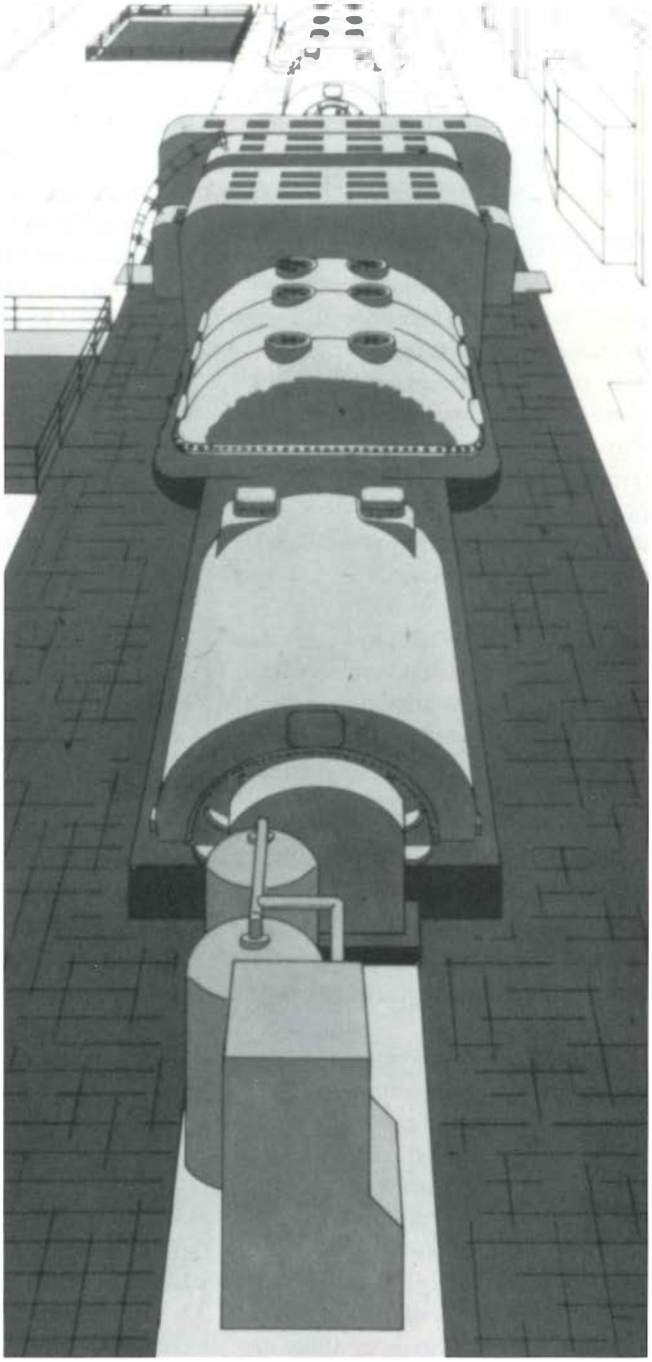
Transmission cable



Energy storage plant



Electric generator

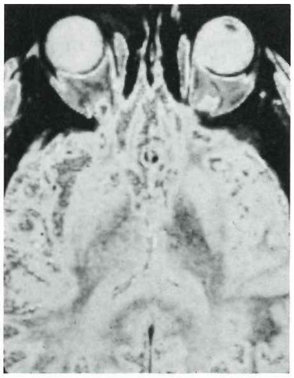


Nonutility Applications

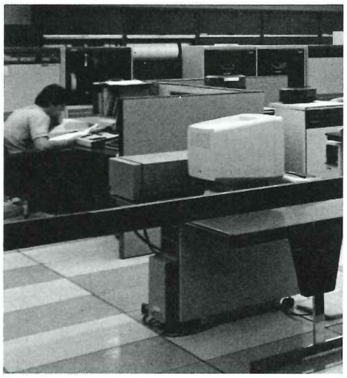
Superconducting devices are already being used in a small number of highly specialized applications outside the utility industry. For example, hundreds of superconducting magnetic resonance imaging devices are sold each year for use in medical diagnosis, and Japan Railways Group has built a prototype of a train that uses superconducting magnets to levitate above its tracks. The development of high-temperature superconductors should greatly expand this range of applications, breathing new life into the effort to create superconducting computers or perhaps sparking the use of intense magnetic fields in manufacturing processes such as metals forming. The superconductors could also lead to development of new magnetic sensing devices of unprecedented accuracy and sensitivity for such diverse fields as petroleum exploration, submarine detection, and brainwave analysis.

Magnetic levitation train

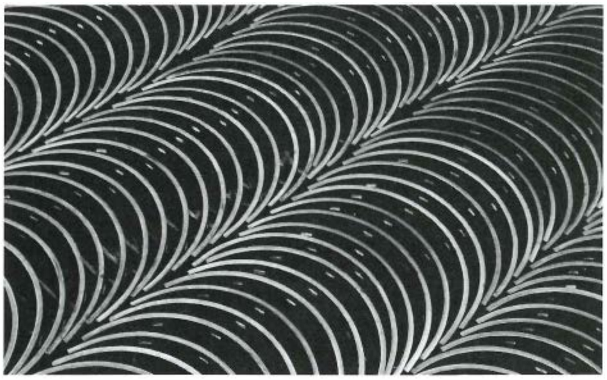
Medical diagnostics



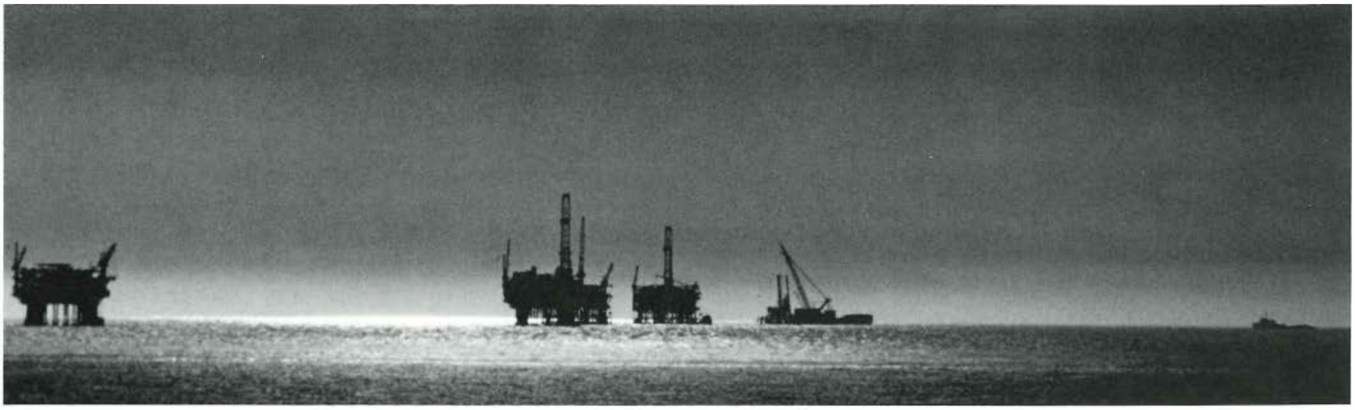
Computers



Metal forming



Geologic exploration



ogy—circuits made with gallium arsenide, rather than silicon—promised to provide faster speed without the nuisance of maintaining superconductivity. Whether ceramic superconductors will make better Josephson junctions remains to be seen, but skeptics point out that their higher temperatures will result in considerably more electrical noise in circuits.

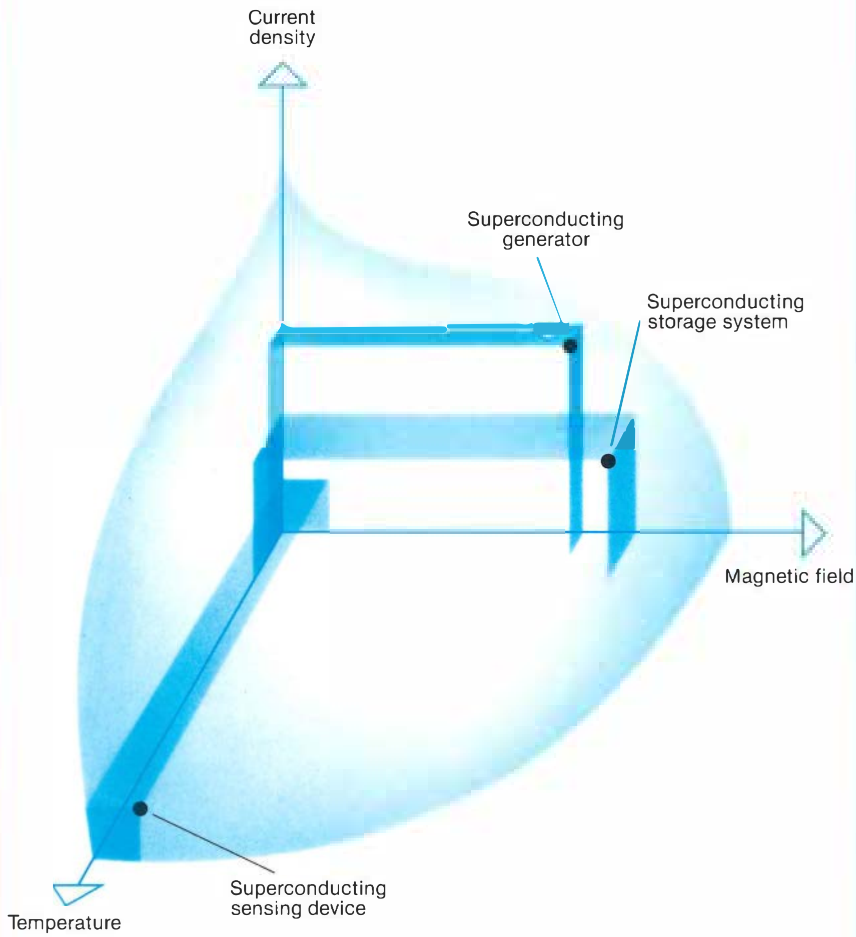
Electric utilities would also benefit if the new superconductors were to increase the demand for power among major customers. A few current applications already illustrate the kinds of new markets that might be opened. Several hundred magnetic resonance imaging (MRI) devices, for example, are now providing unprecedented diagnostic ability to hospitals around the country, using powerful fields from superconducting magnets. A significant fraction of the cost of using MRI (tens of thousands of dollars per machine per year) goes to supplying liquid helium, so switching to a system based on liquid nitrogen might speed the proliferation of this electricity-intensive technology.

Another potential use of superconductors, which is now nearing commercialization and would require considerable electric power, is the magnetically levitated train, or maglev. Such trains use magnetic attraction or repulsion to lift a train and push it along specially designed tracks at speeds of 200–300 miles per hour. Both Japanese and West German companies have produced working prototypes and are now vying to build maglev lines in Nevada and Pennsylvania. Only the Japanese version, however, uses superconducting magnets; the commercial German design is based on conventional magnets. The possible effect of the new ceramic materials in this application remains unclear.

Further in the future, several industrial processes might also be good candidates for high-temperature super-

Technical Trade-offs for Applications

To remain superconducting, a material must be held within a tight envelope of temperature, magnetic field strength, and current density. Trade-offs among these variables can be made for specific applications as long as the three-dimensional plot remains inside the envelope. For example, a superconducting sensing device could be sustained at relatively high temperature because it involves small currents and magnetic fields. Superconducting generators or magnetic energy storage systems, on the other hand, require large currents and fields and so would have to be operated at lower temperatures. The envelope surface shown here is based on the well-understood properties of classical metallic superconductors; the new ceramic superconductors have not yet been fully characterized.



conductors. Already powerful superconducting magnets have shown the ability to separate impurities from coal and clay, and development of a substantially cheaper system using ceramics cooled by liquid nitrogen would probably hasten the spread of this technology. In addition, inexpensive superconducting magnets might find a ready market in forming metals, separating liquids, and growing crystals. Such applications could make industrial processes more productive and lead to increased electrification of the economy.

Utility applications

Of the possible direct uses of new superconducting materials in electric power systems, underground transmission might be easiest to achieve and thus be the first application to benefit. Rights-of-way for new overhead transmission lines are increasingly difficult to obtain, and raising the voltage on existing lines is opposed by those concerned about possible biologic effects of electric and magnetic fields. Yet utilities will face the need to add new transmission capacity in the future as reserve margins decline, as wheeling of power from one service area to another increases, and as pressure mounts to locate new power plants away from urban areas.

Because superconducting underground lines would require large amounts of coolant maintained by refrigeration facilities every few miles, a switch from liquid helium to liquid nitrogen could have a significant economic impact. In some locations underground transmission incorporating ceramic superconductors might become less expensive than the conventional underground cables used today. Considerable development work will have to take place, however, before the new materials are fabricated into sturdy, flexible cables that can be wound on spools for field installation.

A 138-kV prototype superconducting transmission line with alternating current (ac) has undergone several tests at Brookhaven National Laboratory since 1982. The 115-meter cable, whose outer casing measures about 406 millimeters in diameter, contains three conductors of niobium-tin alloy, cooled with liquid helium. The power rating is 1000 MVA, more than three times the capacity of a conventional cable with similar dimensions and voltage. Experience gained in fabricating and testing this line should provide key insights for designing cables that use the new class of superconductors.

"Our hope is that we can lower the cost of superconducting underground ac transmission to make it competitive in the range of 1000 megavolt-amperes," says Ralph Samm, program manager for underground transmission. "The niobium alloy technology would be economically attractive only for lines with much higher capacities, which have a limited market. There is a concern, however, about how well the new superconductors will carry alternating current. Superconducting direct current (dc) lines could be used for very long distances, but the cost of ac-dc conversion would be prohibitive for short lines. We're particularly interested in trying to make ac lines that would be competitive in the 20–30-mile range."

A**NOTHER** utility application stirring considerable interest is the use of superconducting coils to store electricity. Such coils would be charged during off-peak hours by using power from baseload generators, then discharged during peaks, thus reducing the need for expensive cycling power plants. EPRI studies indicate that U.S. utilities could effectively have 6–12% of their total power supply capacity in some form of storage. But only about 3% of utility capacity today comes from storage, almost exclusively as pumped hydroelectric generation.

EPRI recently completed two projects on designing superconducting magnetic energy storage (SMES) systems containing helium-cooled metal alloys. One design represents an engineering test model with a capacity providing 10 MW for two hours. The other involves a full-scale utility storage system, capable of providing 1000 MW for five hours. These studies indicate that even with the more expensive coolant, SMES should be able to compete with battery storage plants for short-term (two to five hours) discharge applications because of its 20% higher round-trip energy efficiency. For longer discharge periods, compressed-air storage and pumped-hydro plants would still have an advantage.

"Ceramic superconductors (if they turn out to be suitable) would probably lower the cost of SMES by 5–30%, depending on whether they were cooled with liquid nitrogen or could be operated at room temperature," says Robert Schainker, program manager for energy storage. "But it's important to remember that even if room-temperature superconductors are developed, we might still want to put them in liquid nitrogen or liquid helium in order to carry larger currents. The energy storage capacity of SMES increases as the square of the current in its coils, so our emphasis is on getting high current."

Quite apart from the superconducting materials or coolant used in SMES, however, any such facility would pose some unique engineering challenges. One important consideration is size—the SMES coil in EPRI's original 1000-MW design, for example, would be about half a mile in diameter. The outer boundary for such a facility would probably have to be more than two

The Quest for Higher Temperatures

The discovery of hot superconductors surprised almost everyone. For years the loss of virtually all resistance to the flow of electric current in certain metals had occurred only at temperatures within about 20 degrees of absolute zero (0 K), the point at which all molecular motion ceases. When the breakthrough to higher temperatures came, the new superconducting media were not metals but ceramics—materials that ordinarily act as insulators or semiconductors at room temperature.

This was not the first time that experiments on superconducting materials had outstripped theory. The phenomenon of superconductivity was discovered accidentally in 1911 by a Dutch physicist, Heike Kamerlingh Onnes. He had developed a method for liquefying helium and found that mercury lost its electrical resistance when immersed in the liquid, which had a temperature of 4.2 K. An adequate explanation of Onnes's discovery did not come until 1957, when John Bardeen, Leon Cooper, and John Schrieffer developed what became known as the BCS theory of superconductivity. The three men later shared a Nobel prize for the theory bearing their initials.

According to the BCS theory, electrons are able to move through a superconductor without resistance because they form pairs that do not collide with surrounding atoms. These so-called Cooper pairs move in tandem along the rows of atoms that make up the crystal lattice of the superconducting material. The usual repulsive force between the electrons in each pair is overcome by their mutual interaction with the atomic lattice.

Superconductivity remained a laboratory curiosity until the early 1960s because the materials used could not carry much current. Then some niobium alloys were found that had high enough current densities to support practical applications. With liquid helium as a coolant, these alloys were eventually used to make superconducting magnets for high-energy particle accelerators and sophisticated medical imaging equipment. Over the years, some progress was also made in finding alloys with higher critical temperatures, the maximum temperature for which superconductivity occurs for a particular material. The best niobium alloys, however, had critical temperatures just above 20 K and showed little prospect of going much higher.

Then, in 1986 Georg Bednorz and Alex Müller at IBM's Zurich laboratories discovered a mixed oxide material that was superconducting at 30 K. The oxide belonged to a family of ceramic materials called perovskites. As researchers worldwide began making variations on the original material, they quickly found perovskites that were superconducting at temperatures up to ~100 K (−280°F), far beyond the limit expected by the BCS theory. (Although ceramic superconductors include so-called rare earth elements, these are, in fact, abundant enough to meet foreseeable demand.)

The search for even better materials has become widespread, and research in the field has taken the form of a latter-day alchemy, resembling Thomas Edison's painstaking work with thousands of filaments for his incandescent lamp. Numerous combinations of materials have been tried, with essentially no guidance from theory. For their part, theorists generally agree that high-temperature superconductivity still results from formation of electron pairs, but they have to find a new explanation for what holds the electrons together as they move through perovskites.

"Several laboratories have found fleeting indications of superconductivity at room temperature, but it appears to occur only across small islands inside the material," says Mario Rabinowitz, senior scientist in the Electrical Systems Division. "Some people think these are only anomalies, but I'm more of an optimist. I believe there's a good chance we'll eventually be able to develop room-temperature superconductors in bulk, especially if a good theory is found to help predict how different materials will behave. Concern has also been expressed about the relatively low capacity of these materials to carry current, but I believe it's reasonable to be optimistic about improving that also." □

miles in diameter because of high magnetic fields. Subsequent designs by other groups could be somewhat smaller, but all involve making large excavations because the coils would push outward with such force that they must be buried in solid rock. In addition, a considerable amount of epoxy and metal framework would be needed to hold the conductor in place.

Technical hurdles

Because ceramic superconductors are so new, relatively little is known about their electrical, mechanical,and chemical properties. If they are to be useful in electric utility applications, however, it is clear that several technical hurdles must be overcome: Current-carrying capacities of the new materials have to be increased, and ways have to be found to fabricate them into useful configurations.

Designing applications for any superconducting material involves a trade-off with three fundamental properties—its temperature, the strength of the magnetic field surrounding it, and the amount of current passing through its cross-sectional area (its current density). Pushing any of these variables beyond a critical point can cause a sample of material to suddenly lose its superconductivity, a process called quenching. Even before the quenching point is reached, however, the amount of current a superconductor can carry decreases as either temperature or the magnetic field increases.

"The problems are linked; for example, to get a large current you may have to cool a superconductor well below its nominal critical temperature," says Dave Sharma, a senior project manager who is helping to coordinate superconductor activities at EPRI. "At the temperature of liquid nitrogen, maximum current densities in ceramic superconductors are now too low for most utility applications by a factor of 10 to 100. Larger current densities have been achieved in small uniform crystals, but we simply don't know yet how high they can go in bulk materials. This issue must be resolved before we can proceed much further with design work. If current densities can be improved, we believe that the first utility application of the new superconductors will be in underground transmission cables."

FORTUNATELY for the work on fabrication, the general characteristics of ceramics are well known, and engineers have many years of experience to draw on. The usual way to produce ceramics in a flexible form, for example, is to fabricate them as thin fibers. The physical properties of ceramics are similar to those of glass—brittle in the bulk form used as windows, but pliable when spun into the glass wool used as insulation. Although ceramic fibers break easily if pulled apart, they don't deform much under pressure.

"Existing technologies to make ceramic fibers should be applicable for producing components for most electric utility equipment from the new superconducting materials," says Wate Bakker, technical area manager for materials support and exploratory research. "Ceramic fibers now made from alumina and silica are really very flexible; you could knit a sweater from them if you wanted. Their high compressive strength means that they can be laminated with metals by cold rolling. It should be possible to make similar fibers from superconducting oxides and laminate them with copper or aluminum."

Such lamination will be an important part of making cables for electrical equipment for two reasons. First, a matrix of ordinary metal, such as copper, provides physical protection to the delicate fibers. This protection is to prevent surface damage during handling, which dramatically decreases the tensile strength of the fiber. Second, the ordinary metallic conductor would help divert potentially damaging current from the fibers if their superconductivity is suddenly quenched. Ceramic fibers with individual diameters of 10–25 micrometers would probably be embedded in a conductor in bundles of about 100.

The primary disadvantage of using conventionally made ceramic fibers is that their microstructure consists of randomly oriented, fine-grained crystals. Inside a uniform crystal, the maximum current density that can be carried along one crystal axis is about 30 to 60 times larger than that which can be carried in a direction perpendicular to that axis. Thus, randomly oriented small crystals carry less current on the average than would be expected in a single large crystal oriented in the right direction.

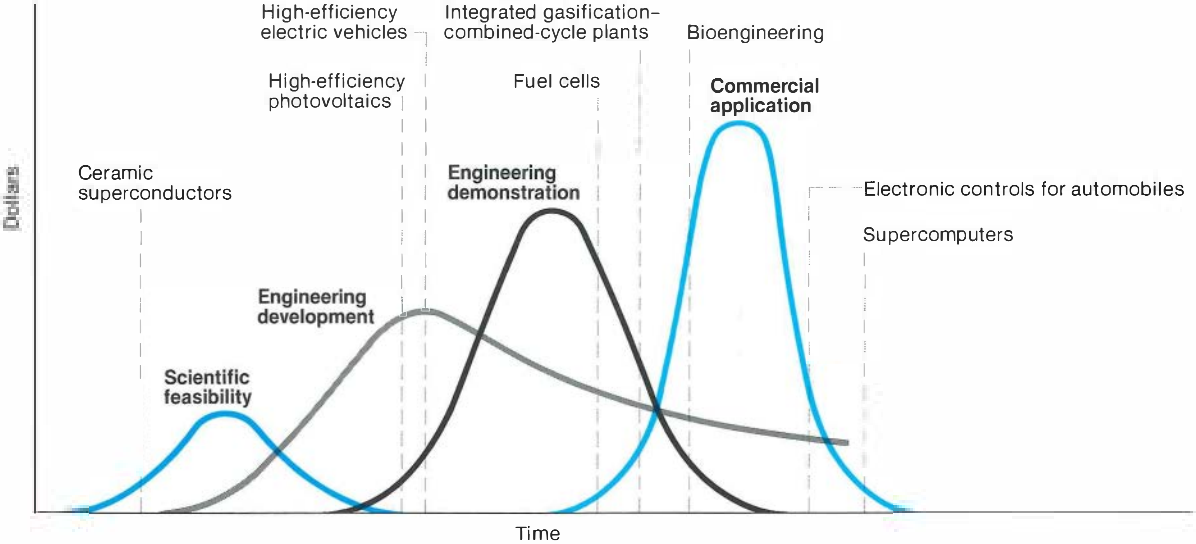
In addition, the boundary regions between crystal grains seem to lower the critical current density of the new ceramics even further and make their superconductivity even more susceptible to interruption by magnetic fields. Whether this effect results from impurities in the boundary regions or is an inherent property of the ceramic crystals themselves remains to be determined. In some small-scale applications, such as fabrication of computer chips, manufacturers can probably avoid this problem by growing large single crystals, but this process would be too slow for making long fibers.

Research strategy

Because of the suddenness with which superconducting ceramics first appeared and the relentless pace of subsequent announcements, research-funding or-

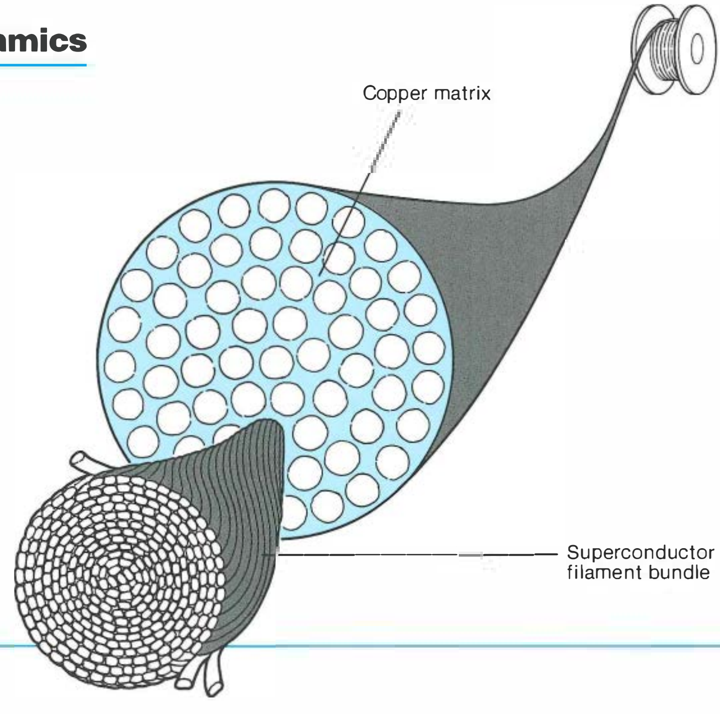
Development Takes Time

Considerable time and money will have to be invested in R&D on ceramic superconductors before they can become commercially successful. The development of any new technology will generally involve four broadly overlapping phases of such work: proof of scientific feasibility in the laboratory, development of a fully engineered product, demonstration of the product at commercial scale, and introduction of the product into commercial use. As exciting and broad as their potential appears to be, ceramic superconductors are still in the earliest stage of development.



Making Wires From Ceramics

For utility applications, ways will have to be developed to fabricate the inherently brittle ceramic superconductor material into flexible wires or ribbons. One possible solution would be to produce extremely fine filaments of the material, which (like spun glass) are much more flexible than the bulk form. These short filaments could be twisted like yarn into bundles, or threads, about a quarter millimeter in diameter and arranged in a protective matrix of copper or other metal. A 3-millimeter superconducting wire might contain 70 or 80 bundles of perhaps 500 filaments each.



ganizations face the need to establish rational strategies for pursuing practical applications of this scientific breakthrough. On the one hand, so little is known about the new materials and their possible limitations that an immediate massive commitment of R&D resources would seem premature. On the other hand, the potential effect of high-temperature superconductors could be so profound and the international competition to exploit them is already so intense that a dynamic, coordinated research approach has become imperative.

"A national R&D strategy on superconductivity is beginning to take shape," says Narain Hingorani, vice president and director of the Institute's Electrical Systems Division, "and EPRI is participating on behalf of the electric utility industry. We've been holding talks with the National Science Foundation and the U.S. Department of Energy on how best to organize our resources and coordinate our research efforts.

"Such united action is needed to prepare for a long-term effort and to meet the challenge of foreign competition," points out Hingorani. "Experience tells us that at least a decade will be needed before products made from these new materials are ready for the utility market. EPRI's role will be to look at the full research picture, act as a catalyst in technology development, and make sure that applications are responsive to utility needs."

Some EPRI-sponsored research is already under way, and other specific projects are being planned. The Electrical Systems Division is now conducting two technical assessment studies: one at Los Alamos National Laboratory (LANL) and one at Reliance Electric. The aim of these studies is to evaluate the potential application of high-temperature superconductors to underground transmission systems and to motors and generators. Results are expected by the end of the year. A third project, now piggybacking on other work at LANL, involves measuring ac losses in the new materials and investigating ways to increase their current densities.

The Advanced Power Systems Division is exploring various options for funding new work on superconducting magnetic energy storage. One possibility is a joint effort with the U.S. Department of Defense. Superconducting power storage has particular interest for the Strategic Defense Initiative because laser weapons need such large quantities of power so quickly. "This program, if approved, would combine utility and SDI applications research into a coordinated program," says Robert Schainker.

Research on materials characteristics and exploration of alternative fabrication techniques for ceramic materials is being initiated by EPRI's exploratory research group. Progress in understanding the materials, their potential for improvements, and fabrication methods that increase stability and performance is essential before the suitability of ceramic superconductors for electric power applications, such as transmission cables, magnetic coils, and other utility equipment, can be assessed and exploited. The Energy Management and Utilization Division has initiated a key study jointly with DOE to identify end-use applications of superconductivity that could benefit electric utilities and their customers.

"Our challenge in the end-use area is to look for new opportunities that high-temperature superconductors can provide, rather than see these materials only as substitutes for conventional superconductors in their present uses," says Fritz Kalhammer, vice president and director of the Energy Management and Utilization Division. "I believe their greatest effect will come not by changing the way we make present-day equipment but rather by creating productive new uses for electricity where none existed before. But first we have to answer a number of rather basic questions about these materials and find ways of fabricating them in useful forms."

Throughout the Institute, news of the discovery of high-temperature superconductors has been greeted with a mixture of caution and excitement: caution born of long experience with complex technologies, including superconductivity; excitement stemming from the potential that better superconducting materials might have for fundamentally changing electric power systems. Although the technical challenge is an engineer's delight, the succession of unsubstantiated or difficult-to-reproduce claims is a source of concerned skepticism for planners.

"We're prepared to roll the dice in this area," says Richard Balzhiser, EPRI's executive vice president for R&D. "All research involves risk, but I believe the potential importance of high-temperature superconductors to the electric power industry certainly justifies committing significant resources, even at this early stage in the game. We have to proceed cautiously, however, beginning with a realistic evaluation of the potentials and seeking partners among other funding agencies. The payoff will not come quickly, but it may be quite substantial." ■

This article was written by John Douglas, science writer. Technical information was provided by Frank Young, Mario Rabinowitz, Dave Sharma, Ralph Samm, J C. White, Electrical Systems Division; Wate Bakker, Energy Management and Utilization Division; and Robert Schainker, Advanced Power Systems Division.

TOXIC RESEARCH AND THE REAL WORLD

Analyses of the environmental effects of pollutants have often ignored real-world conditions and relied almost exclusively on laboratory studies. New interdisciplinary approaches are factoring in insights from field research to yield more-realistic ecologic assessments.

Like the fabled blind men who perceived the elephant to be nothing more than the leg or trunk or tail that they had touched, scientists historically have studied the toxicologic effects of pollutants in isolation from the larger body of the environment. To see if they are harmful, suspect materials are applied to test organisms under strictly controlled conditions in a laboratory or field plot. Extrapolating from the relation between dose and response in such experiments, researchers form an image of how the substance might appear and behave in the environment. Sometimes they are right. Other times, they draw conclusions like that reached by one of the blind men: elephants are long, squirmy, peanut-loving tubes. Partially true, but not the whole picture.

The pesticide DDT provides a well-known example of how, by failing to recognize the complexities of ecologic systems, scientists can make mistakes in judging a substance's environmental effects. Researchers developed DDT to kill insect pests but as it turned out, it did more than that. It killed beneficial insects that pollinate crops and prey on pest species. Moreover, DDT broke down into compounds that were taken up by microorganisms and concentrated as they passed through the food web, causing reproductive failure, lowered disease resistance, and metabolic disruption in numerous species of birds. Regional populations of several endangered species, including the peregrine falcon, nearly disappeared, largely because of DDT contamination. As the full environmental hazard of the chemical became apparent, it was banned in the United States.

With this and other lessons learned the hard way, researchers realized that they had to start considering pollutants and organisms in the context of their abiotic and biotic environments. They had to ask new questions: How do the physical and chemical properties of the air, soil, and water influence the solubility, transport, and toxicity of a pollutant? How are the form and concentration of the pollutant modified through the food web? If more than one pollutant is present will they interact? If so, will their cumulative effect be greater or smaller than each of them acting in isolation?

Recognizing that the traditional dose-response experiments are too narrowly focused to deal effectively with such questions, ecologists, geochemists, and toxicologists in the past two decades have begun to collaborate. They are developing new interdisciplinary research techniques to help them predict more accurately the environmental impact of pollutants across a wide range of conditions. Such predictive power is invaluable in sorting out—for various environmental conditions—which pollutants pose serious hazards, which do not, and what levels of protective standards and mitigation efforts are warranted. This is good news for utilities and other industries, which have a strong interest in seeing that the environmental regulations they operate under are based on rational, accurate assessments of pollutant effects.

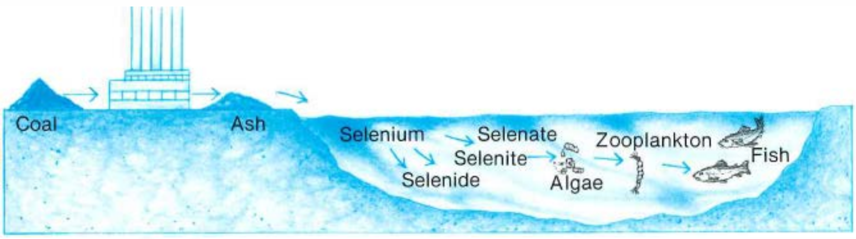
A new research strategy

"Pollution effects research should be pursued on three levels," explains EPRI's John Huckabee: "cycling, effects, and assessment." Cycling research—known also as biogeochemistry—involves monitoring the flow of a substance through the various compartments of the ecosystem (soil, water, air, plants, animals). The mass of a substance (such as carbon, nitrogen, mercury, selenium) introduced to the system and the rate at which it flows among the compartments can be expressed mathematically. Many such equations can be linked together to form a quantitative, mechanistic model of material cycling through the environment. The model can then identify imbalances in the pools or flows of key elements in the system (more lead than usual in animal tissues, for instance), which indicate the need for a toxicity test.

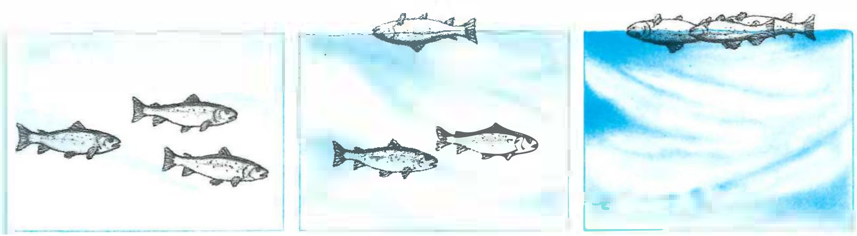
A Three-Pronged Approach

Scientists are combining cycling research with effects studies to yield the insights needed for realistic assessments of pollutant impacts.

1. The cycling studies measure pollutants released to the environment and track them as they interact with other substances, change form, and pass through the food web. Such studies reveal which forms of a pollutant are most likely to be prevalent and of potential concern in the field. Selenium, for instance, appears in three principal forms that vary widely in biologic uptake and toxicity.

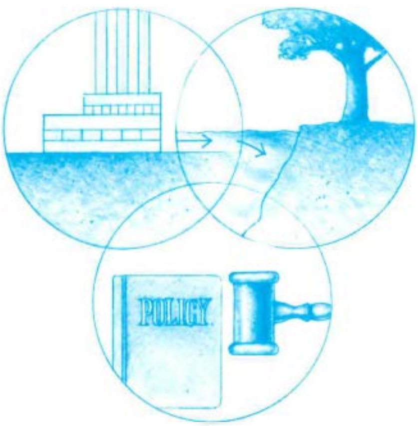


2. The effects studies, in contrast to the broad focus of cycling research, are conducted under strictly controlled conditions to test the response of organisms to varying doses of a specific pollutant. Effects studies are very useful for testing toxicity, but they sometimes are applied to the wrong substance. This pitfall can be avoided by running cycling studies in parallel to reveal which toxicants are most likely to occur in the environment and should thus be tested for toxicity.



Low dose, high survival | Moderate dose, moderate survival | High dose, low survival

3. The assessment tier of pollution effects research integrates all the findings from cycling and dose-response studies into a framework that is useful to policymakers. The integrated lake-watershed acidification study model, for instance, has been used to assess how various levels of power plant emissions will affect regional environments. Such insights can form the technical basis for decisions on emission control strategies.

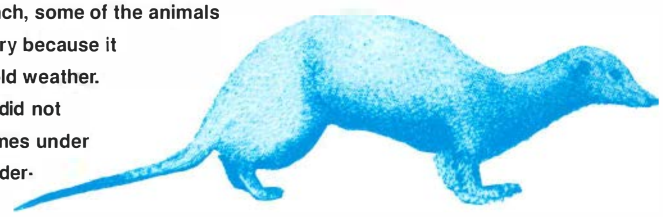


The toxicity test is the "effects" tier of the research strategy. Here, researchers conduct controlled dose-response experiments using bioassays, microcosms, and field plots. "There should be an iterative relation between cycling and effects research," adds Don Porcella, who manages aquatic ecology research at EPRI. "Toxicity experiments should draw on field measurements gathered in the cycling research to determine the forms and concentrations of pollutants to test. Conversely, biogeochemical studies can be focused on the compounds of greatest concern by drawing on what is already known from toxicology."

The third research level, regional assessment, draws together all the insights gained in the cycling and effects work to determine the overall ecologic impact of a pollutant or pollutants. The types of soils in a region and the typical range of acidity in rivers and streams, for instance, bear strongly on the chemical forms that a given pollutant will assume and whether it will be taken up in the food web or immobilized in bottom sediments. With such insights on cycling and with the results of targeted toxicity tests on those chemicals that are likely to appear, analysts can predict how the various forms of a given pollutant will be apportioned chemically and biologically, how likely they are to reach toxic concentrations, and what impact various mitigation or control options will have. Such assessments can then serve as the scientific basis on which to develop environmental regulations and standards.

Mink and Mercury

Experience from separate studies of mercury's effects on mink illustrate the importance of an integrated real-world approach to pollutant-effects research. To determine whether mercury in fish fed to mink harmed the animals, researchers fed laboratory mink a diet containing 1.1 part per million of mercury. No clinical effects were apparent and there were no fatalities. In a later study conducted at a mink ranch, some of the animals died when fed 1 ppm of mercury because it inhibited their resistance to cold weather. Because the laboratory study did not consider the temperature regimes under which mink must survive, it underestimated the danger posed by mercury contamination.



A track record with acid rain

EPRI's research on the ecologic effects of acid rain illustrates the value of integrating biogeochemistry with toxicity analyses. The Integrated Lake Watershed Acidification Study, completed in 1984, generated a model that has been widely used by utilities and government agencies in making assessments of acid rain impacts. The ILWAS model traces the flow of water and dissolved substances through the watershed. Given values for precipitation, acid deposition rates, and various biogeochemical parameters like the depth and buffering capacity of the soil, the model predicts the level of lake acidification and the likelihood of damage to the aquatic ecosystem.

Northern States Power recently used the ILWAS model to help evaluate the environmental consequences of various options for controlling coal-plant SO_2 emissions. According to Joe Wolf, NSP's Manager of Environmental Sciences, "ILWAS played a central role in convincing the state of Minnesota to retract its requirement that we add scrubbers to two existing coal plants. The model helped show that we could obtain comparable environmental benefits at far less cost by switching to low-sulfur coal. By avoiding the scrubbers, NSP and its customers saved more than $200 million."

Another series of EPRI projects studying aluminum exemplifies this linking of cycling and effects. Together they are investigating the aluminum mobilization hypothesis, one of the suggested mechanisms linking acid deposition with forest decline and fish losses. The hypothesis asks whether aluminum, mobilized into toxic forms in the soil by acid rain, damages tree roots and washes into lakes where it reaches levels toxic to fish.

Several projects are measuring aluminum toxicity in field and laboratory studies. Results from this work are being incorporated with biogeochemical data to provide a quantitative, systematic analysis of the links between atmospheric pollution and aluminum toxicity to trees, fish, and other aquatic life.

Applying the method to solid wastes

A similar approach is being applied in EPRI's study of toxicants potentially mobilized from coal ash and scrubber sludge. The list includes a number of trace metals, including cadmium, selenium, chromium, and arsenic. These elements are potentially toxic in certain forms and concentrations, but little is known about their geochemistry and their ability to migrate through soils and groundwater.

Utilities produce more than 70 million tons of ash and about 7 million tons of sludge each year. Whether disposed of or marketed for secondary use, the large volumes of these materials make it very important that their properties and any potential related environmental problems be well understood.

EPRI is therefore sponsoring several studies on the release, transport, and transformation of chemicals from utility solid wastes. This research is digging into the nitty-gritty of groundwater hydrol-

Selenium: How Much Is Too Much?

Selenium is a particularly challenging element to study. Occurring naturally in soils, it is an important nutrient in trace amounts, but it can be toxic in certain forms at high concentrations. In the log of his thirteenth century journeys, Marco Polo recorded that when his pack animals grazed on a particular plant in western China they got sore hoofs—a disorder characteristic of selenium poisoning. Selenium toxicity also may have played a role in General Custer's defeat at Little Big Horn; cavalry sent to reinforce Custer's army were delayed by sick horses who had been feeding on plants growing in selenium-rich soils. And several years ago selenium washed from agricultural soils made headlines by killing fish and water birds in the Kesterson National Wildlife Refuge in California.

Ironically, selenium is also an important nutrient for animals and people. It is added to cattle feed in areas with selenium-deficient soils, and people consume it regularly in vitamin supplements. A form of congestive heart failure in children and young women in parts of China has been associated by some researchers with selenium deficiency.

The element is not unique in being a nutrient in small doses and a toxin in high concentrations—many compounds share that distinction—but with selenium the line between too little and too much is unusually narrow. This fine line makes it particularly important that we understand enough about the element to set rational standards.

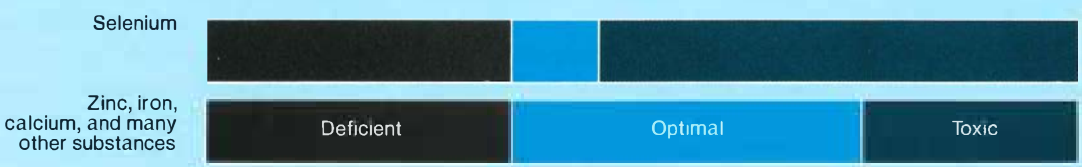
Utilities are concerned about selenium because it is present in fossil fuel ash and scrubber sludge. It has been associated with the loss of fish populations in cooling reservoirs adjacent to coal-fired plants at three sites in North Carolina and Texas. (Water from ash disposal ponds drained into the reservoirs, carrying small amounts of selenium and other metals.)

Once selenium was implicated, standards for maximum total concentrations of the element in aquatic ecosystems were set in North Carolina. Rather than focusing on partial control options designed to meet just the selenium standards, the North Carolina utilities involved decided to eliminate releases of all ash contaminants to the reservoirs by switching from ash ponds to dry disposal in landfills. Duke Power has done this already at the Belews Creek station and Carolina Power & Light expects to complete similar changes at its Roxboro station within several years. Faced with similar conditions, the Texas Utilities Generating Co., under agreement with the state, installed a water treatment plant to remove trace metals from the ash pond water at its Martin Lake station. The capital cost of these modifications at the three sites will total a hefty $65 million.

Are such large expenditures needed to achieve the desired level of environmental protection? That's the 65 million dollar question, and the stakes could rise even higher if similar control measures are required at more of the 1000-plus utility waste disposal sites around the country.

EPRI's research on animal response to interacting stress (ARTIS) may confirm that the existing selenium standards are at about the right level for protecting aquatic systems (fish are returning to the two ponds where selenium releases have already been controlled). Or the evidence may indicate that stricter or more lenient levels are appropriate under various conditions. Whatever the results, by unraveling the mechanisms of selenium cycling and toxicology, ARTIS will bring a new level of scientific understanding to the regulatory process. □

Many substances, even water, are essential to life in small-to-moderate amounts but are toxic in high doses. For selenium, the line between deficiency and toxicity is a fine one, complicating the task of setting standards for acceptable concentrations of the element.



ogy, soil physics, and geochemistry. Data developed in 1986, for instance, showed that chromium, a trace metal in coal wastes, is effectively immobilized in most soil conditions. It can be oxidized to more-toxic forms by manganese dioxide, however, suggesting that wastes high in chromium should not be placed in manganese-rich environments. These are the kinds of detailed analyses needed to evaluate and refine the do's and don'ts of waste management. Without such detail, engineers have little basis for determining how to control the by-products of electricity production and protect the environment in a cost-effective way.

The effects of multiple ecologic stresses

Quite frequently, ecologic systems are stressed by a number of factors, some of which interact in ways that strengthen or reduce their combined effect. Mechanistic environmental models are particularly useful for understanding such phenomena because they explicitly consider the added complexity of biogeochemistry, food web interactions, and toxicology that multiple stresses involve.

EPRI recently launched a $7 million, four-year project known as ARTIS (animal response to interacting stresses) to study such effects on aquatic ecosystems. The project will focus primarily on selenium's impact on fish and food web organisms but will also study arsenic, mercury, and geochemical parameters that can act as stressors in their own right, including acidity, temperature, and dissolved oxygen.

The mercury studies will seek geochemical explanations for the fact that the element sometimes bioaccumulates quite dramatically. Fish living in waters where mercury concentrations are barely detectable can nevertheless develop levels of mercury in their tissues that are dangerous to humans who consume the fish. In other settings, tissue levels may be fairly low, even in waters containing lots of mercury. "Mercury changes form very rapidly," explains Huckabee, "and we need to understand the cycling a lot better if we are to minimize its deleterious environmental impacts."

Selenium is another moving target that ARTIS will try to pin down. "The biogeochemistry of selenium is quite complex," explains Porcella. "It occurs in different forms, or species, of varying toxicity whose relative distributions depend in part on the levels of other compounds in the water. High sulfate concentrations, for instance, may inhibit biologic selenium uptake. And nutrient levels influence the productivity of phytoplankton, which in turn affects the rate of selenium cycling through the system. Selenium also interacts with other toxicants. It reduces net mercury uptake by organisms, for instance, through mechanisms that are not yet fully understood."

ARTIS researchers are pioneering some new analytic techniques that are making it possible for the first time to measure environmental concentrations of the various forms of selenium, arsenic, and mercury. Previous techniques could measure only total elemental concentrations, which were often used as the basis for environmental regulations, even though such readings have little bearing on toxicity.

The new analytic methods rely in part on cross-checking between levels of compounds whose chemical behavior is linked, such as selenium and arsenic. Under known laboratory conditions, chemists expect a certain distribution of the various forms of the two metals. By comparing these laboratory values with the distributions measured in lakes, researchers will begin to understand the biogeochemical factors that control the elements' speciation in nature. Measures of one element can be used to predict or validate the levels of the other element. In the future this kind of linked analysis will be applicable to a wide range of other toxicants.

Guided by what the biogeochemical studies reveal, ARTIS researchers plan to begin toxicologic effects studies for selenium in 1988. Fish will be exposed to different selenium species in regimes closely duplicating actual conditions. The results will then be used to form equations describing what's likely to happen to fish in different kinds of lakes at varying levels of exposure.

This type of predictive model will be invaluable for agencies throughout the country that are trying to set protective standards for aquatic ecosystems. The research may reveal, for instance, that selenium toxicity is less likely in alkaline waters that are high in sulfates than in softwater lakes with relatively few dissolved minerals. Such insights may suggest, for example, that multiple standards tailored to different systems may be more effective than a single regulation applying to all conditions.

"Overprotecting and underprotecting the environment are both very costly," Porcella observes. "Society has limited resources for environmental protection and it is important they are allocated wisely. The more we understand about how pollutants behave in the environment the better we'll be at finding cost-effective solutions." And the less our regulations will resemble the blind men's descriptions of the elephant. ■

Further reading

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Speciation of Selenium and Arsenic in Natural Waters and Sediments, Vols. 1 and 2. Final reports for RP2020-1 and -2, prepared by Old Dominion University and Battelle, Pacific Northwest Laboratories, June 1986. EPRI EA-4641.

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This article was written by Michael Shepard. Technical background information was provided by Donald Porcella and John Huckabee, Environment Division.

High-Sulfur Test Center

DEVELOPING THE NEXT GENERATION OF SULFUR CONTROLS

EPRI's eighth specialized R&D center officially starts work this month, testing and scaling up emissions cleanup systems for plants that burn high-sulfur coal.

"The next generation of scrubbers will have to be designed and run with an eye to the character of their solid by-products and the amount and quality of wastewater," insists Stu Dalton, who manages EPRI's program of research in desulfurization processes. "If not, some designs just won't get permits under one or more local environmental regulations. We've *got* to integrate, and we *can* cut costs."

A major focus of EPRI's R&D response to that need is now in operation. Started up last April and scheduled for dedication late this month, EPRI's High-Sulfur Test Center (HSTC) is well equipped to develop and test a number of processes and systems that combine the control of gaseous emissions, particulate matter from coal combustion, solid wastes, and wastewater.

Further, as its name implies, HSTC zeroes in on the needs of utilities that burn high-sulfur coal. Built alongside the 640-MW Somerset station of New York State Electric & Gas (NYSEG), about 45 miles northeast of Buffalo, the new center draws approximately 28,000 ft^3/min of flue gas (about 1% of the total stream) for treatment in one or another of the laboratory and pilot-scale scrubbers, a spray dryer, an electrostatic precipitator, and a fabric filter. Scrubbing water can be drawn from any of several systems in the Somerset plant, it can be trucked in from other plants, or it can be formulated to order—a feature that permits research on optimized water and energy use.

Environmental protection is one strategic reason for HSTC; the debate over acid rain is stimulating development of new, cost-effective alternatives for power plant emission controls. Another reason is the utility industry's strong, continuing reliance on coal for power generation. Utilities must work toward less complexity and lower cost in emission controls, particularly for plants fueled with high-sulfur coal.

Clean coal technologies are now being demonstrated that combine the suppression or removal of gaseous pollutants with a gasification or fluidized-combustion process. More-efficient interfacing of some or all the emission control processes of future pulverized-coal plants is similarly seen as a desirable move toward better environmental and economic performance.

In addition, prudence suggests developing a range of sulfur removal options, for both new and retrofit plants and for cost-effective use with different fuel sulfur contents. For example, a plant with considerable remaining life might best be served by a system that has very low operating costs per ton of SO_2 removed; another plant, with a relatively short remaining life, would need a system having low capital cost.

These needs and potential solutions have focused attention on the HSTC research program and stimulated support for it. In particular, the selection of NYSEG as host utility and cosponsor drew funding and participation by two other New York institutions, the Empire State Electric Energy Research Corp. and the New York State Energy Research and Development Authority. This year, Consolidation Coal also became a participant. And the Department of Energy, which often independently supports EPRI contractors, has announced that it intends to fund the EPRI project directly.

The role of HSTC is to test new emission control technology at bench and/or pilot scale: proving out hardware—especially control equipment—optimizing its operation, and learning to control it efficiently and reproducibly. "HSTC is a place to develop processes and validate chemical process models," says EPRI's Dalton, "so they can be used to improve reliability and cut costs in commercial plants."

Designing for the future

As EPRI's eighth R&D center, HSTC originated in 1980. When planning began, it focused mainly on wet scrubbing processes and on what Dalton calls efforts to "speed up the learning curve." But EPRI and its consultants, Radian Corp. and Stearns-Roger, saw additional needs, including new problems created in part by increasingly stringent environmental control requirements.

"One example was—and is—more closure of the water loop, with less waste. The result," recalls Dalton, "is chloride buildup that doesn't become apparent until water balances are very tight. Then it makes for additional corrosion, and it can affect performance, too.

"Another problem is progressively higher standards for by-product purity. Permanent disposal in landfills is still common, but by-product salability is getting a much closer look as disposal and treatment costs go up. This also means pressure to see what can be recycled in treatment processes."

EPRI looked hard at its own experience with test center R&D. One example was the Arapahoe Test Facility in Denver, where a 110-MW power plant fueled by low-sulfur coal has furnished flue gas for EPRI's emission control R&D since 1977. First used for urgent study and development of electrostatic precipitators and fabric filters, Arapahoe later added R&D on other emission controls, but the facility's low-sulfur flue gas limits its role in solving high-sulfur emission problems; even its fly ash chemistry is different. In addition, the host Arapahoe plant is in service less frequently today.

A comparable new center, therefore, had to be located at a high sulfur coal–fired plant, preferably one that would operate around the clock with a high availability factor. This would reasonably ensure the conduct of long, uninterrupted test runs.

Other EPRI field experience added weight to the decision for a second dedicated center. Single-purpose pilots tend to be expensive, and sites have been difficult to find for all the work that is planned. Moreover, most sites lack space for modification or expansion. "In short," observes Dalton, "we needed a flexible situation, where we wouldn't be locked into a single arrangement for each piece of work."

In addition, there is day-to-day efficiency that comes with a single operating team and a single O&M group. Despite the $21 million capital cost of HSTC, Dalton estimates that it will save EPRI some $2 million annually, in comparison with an equivalent number of pilot installations at different plants.

Chuck Dene, the project manager during construction, was responsible for the conceptual design of HSTC and also was closely involved during startup. Cost estimates (for the wet scrubber R&D facilities) were completed in 1983, enabling EPRI to select the host utility and Gilbert Commonwealth, the architect-engineer, to begin engineering design in 1984. Ground was broken in 1985, and even though the spray dryer was added only that year, major equipment was on the site in the spring of 1986; HSTC was completed early in 1987.

State-of-the-art flue gas

Somerset is a three-year-old plant on what is termed a grass roots site. "That section of the Lake Ontario shoreline is a fairly pristine area," Dalton explains, "creating a special challenge to keep it that way. So the plant is state-of-the-art in its environmental provisions—low-NO_x burners, scrubbers, extensive water treatment, rigorous landfill design, groundwater quality monitors, the works."

He adds that NYSEG devoted design effort specifically to noise abatement and even received regulatory approval on appropriate exterior colors. "NYSEG has been a good neighbor to nearby communities and groups," Dalton concludes, "and we expect to continue that practice in our work there."

Somerset is also state-of-the-art in its performance. Well maintained and controlled, running at high availability and capacity factors, the plant has registered one of the 20 best heat rate averages in the United States. It is the only scrubber-equipped plant in that grouping.

Somerset burns mostly Pittsburgh No. 8 coal from a Consol mine in West Virginia. However, NYSEG's operating and procurement practices call for periodic test burns of other coals and renegotiation of its fuel supply contracts. These facts add latitude to EPRI's research plans at HSTC.

"Moreover," says Dalton, "the center was designed so that we can take our flue gas before or after Somerset's preheater;

Touring the Test Center

1 NYSEG's Somerset station (right rear) and its flue gas cleanup systems (right foreground) dwarf the High-Sulfur Test Center (left). Their essential connection is the shiny ductwork that supplies flue gas from the Somerset boiler and then returns it to the stack.

2 The absorber vessel of the 4-MW pilot wet scrubber stands among a maze of ducts that route flue gas among alternative combinations of cleanup equipment.

3 An integral part of the test center controls, digital computers enable EPRI research contractors to adjust test conditions, visualize process schematics, review real-time data, and adjust process parameters during the conduct of tests.

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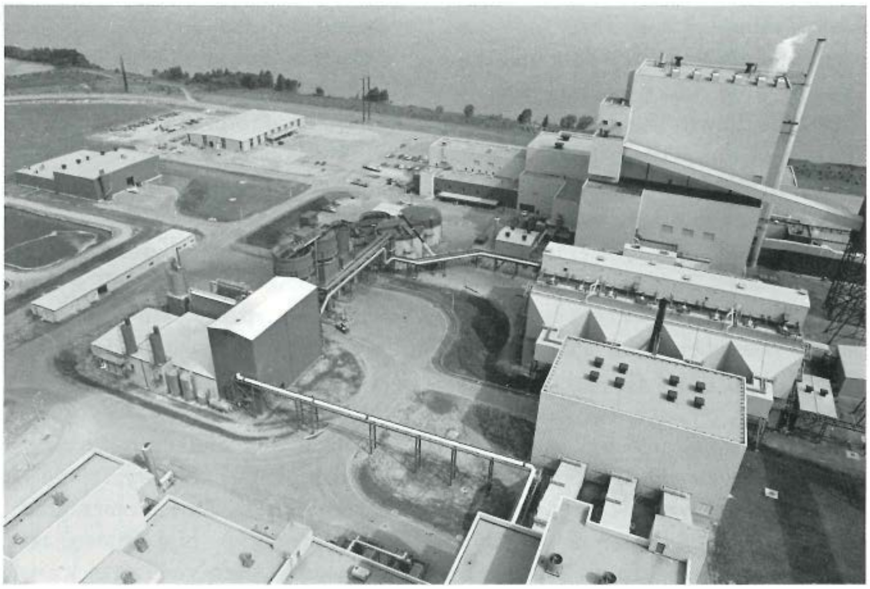

2.

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we can alter the temperature and the particulate loading ourselves, as well as the oxygen content. And if it's helpful on a test, we can spike the gas with extra SO_2 up to a concentration greater than 4000 ppm—say, in the range equivalent to 4.5–5.0% sulfur."

Even that isn't all. Selective access to Somerset's different water systems also adds research flexibility. Referring to the practice of cascading water use (where water is reused in successively less-sensitive applications), Dalton offers a basic description of how system integration leads to operating economy.

"Wet scrubbers, and also spray-dry systems, are a convenient way to evaporate wastewater," he explains. "The trick is to decide which water stream to use and how not to upset your scrubber chemistry with any of them.

"When water evaporates in a scrubber," he goes on, "it doesn't have to be disposed of some other way, and it uses heat that otherwise would go unused. You wind up with a smaller volume of solid waste or by-products, and you also conserve salable energy."

Extensive testing of such wastewater reduction and even zero-discharge techniques will be helpful to midwestern and eastern utilities. Somerset offers plenty of water for the purpose. In contrast, EPRI's Arapahoe facility in Denver copes with the western problem of water scarcity. "At pilot scale, of course, it's possible to fake an adequate water supply," says Dalton, "but most of Arapahoe's research incorporates water conservation."

Operating with flexibility

Occupying a two-acre site alongside Somerset, HSTC features a 26,500-ft^2 building with 6000 ft^2 of laboratory area, a machinery bay, and (to begin with) five pilot-scale emission control systems, plus necessary storage tanks.

Two of the systems, an electrostatic precipitator and a baghouse, provide particulate control for separate exhaust flows equivalent to about 5 MW of generating capacity. Flue gas can be ducted to pass through one unit or both, in either sequence, before or after scrubbing. Dalton notes that a pulse jet filter will be added later—a fabric filter supported by a cylindrical cage and cleaned by periodic high-pressure air pulses that dislodge the filter cake for collection while the filter remains in service.

Two more systems now in place are wet scrubbers, a 4-MW pilot unit and a 0.4-MW minipilot unit. These units have been carefully sized. The pilot unit is the smallest from which scaleup data can reliably be drawn. The minipilot, a tenth the size of the pilot, is the smallest at which an integrated process can be operated with commercially available equipment.

There will also be a bench-scale scrubber in the laboratory, able to treat a 5-ft^3/min flow of real or simulated flue gas. HSTC is thus the first research facility equipped with three levels of wet-process flue gas desulfurization available for performance comparisons, and Dalton makes a point of how these can be used. "Work can be scaled up or down from one scrubber module to another. If an additive doesn't work as expected in the 4-MW pilot, we can step back, even to bench scale, in the course of making process adjustments."

The fifth main pilot system is a 4-MW spray dryer. This kind of equipment has seen some commercial use for SO_2 removal in low-sulfur coal applications. HSTC research seeks to evaluate and adapt it for use with high-sulfur flue gas. And because scrubbers are the traditional focus of Dalton's program—"where the alkaline slurry meets the acid gas," as he puts it—he also calls attention to equipment that has been added for testing totally dry sorbent processes.

"Say a power plant has an electrostatic precipitator, an ESP, that is marginal for one reason or another, such as its age, a different coal, or more-restrictive environmental standards. The dry process called Hypas might be a way to boost that plant's performance in particulate removal and get SO_2 out too."

Hypas (hybrid pollution abatement system) combines electrostatic precipitation and fabric filtration with an intervening stage, where a finely milled dry sorbent is injected into the flue gas. The sorbent captures some SO_2 in suspension and is in turn captured at the baghouse, where it continues to function in the form of filter cake.

"Electric Power Technologies and Southern Research Institute worked out the Hypas concept," says Dalton, "and we'll develop it for utility use. HSTC is the place to verify the process under authentic conditions."

HSTC auxiliaries include reagent preparation equipment (ball mill and paste slaker, with space for a third mill), a sludge reaction tank, and several dewatering alternatives: thickener, belt filter, centrifuge, and hydrocyclone.

Summarizing and characterizing the HSTC equipment inventory, Dalton again emphasizes flexibility. Momentarily using the stereotype of a Chinese restaurant menu, "where you can pick any option from Column A and combine it with any option from Column B," he methodically recapitulates the way in which every subsystem can be varied or substituted: flue gas, particulate control, water supply, scrubber reagent (and its preparation), by-products, and wastes.

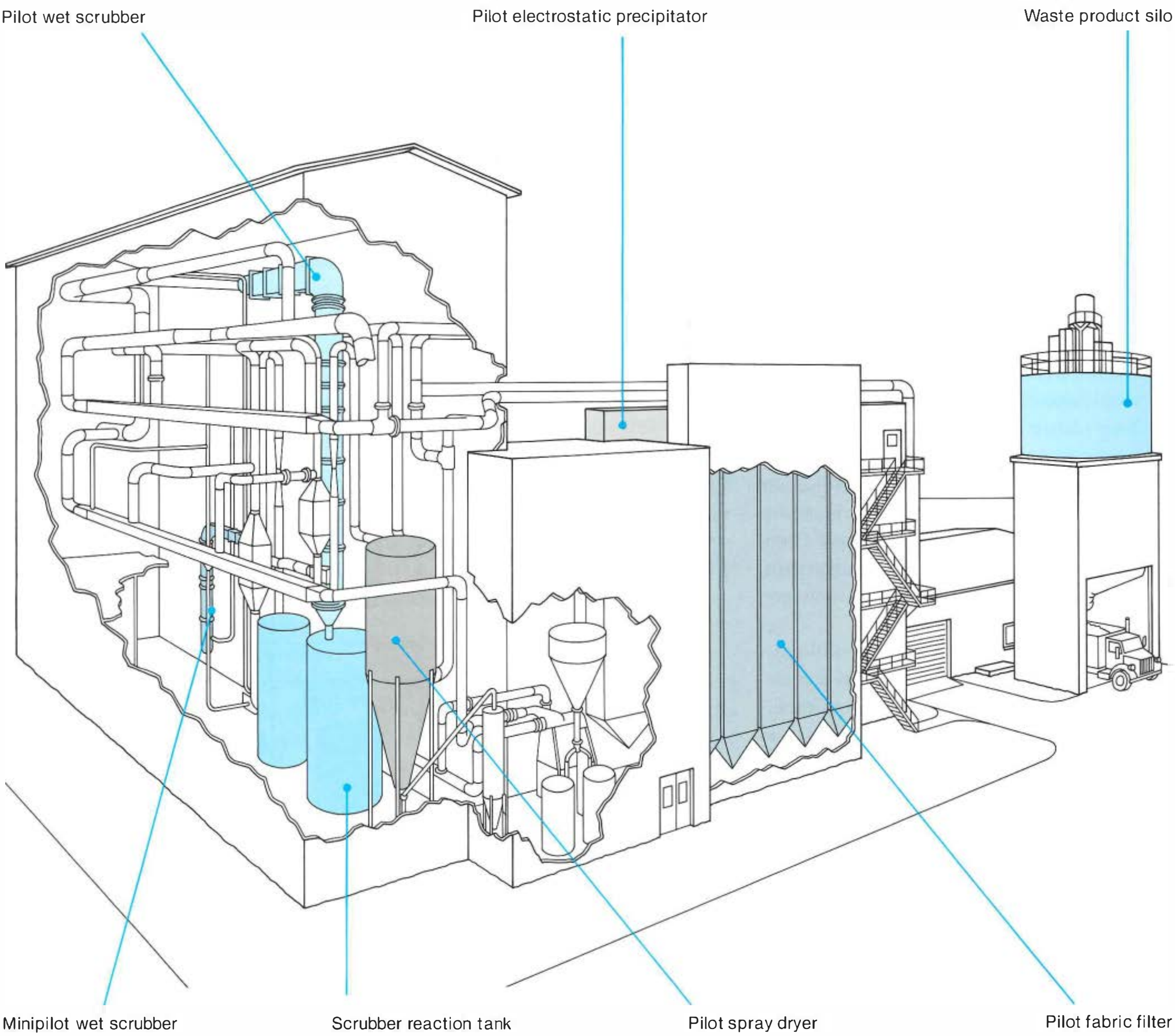
Cooperative management

Robert Glover is EPRI's resident manager at HSTC, building on earlier experience with one of EPRI's research contractors at Arapahoe. He has been at HSTC since construction began, and he now oversees the work of EPRI's operating contractor, Gilbert Commonwealth, and its three-shift staff of about 30. Glover also coordinates the visiting test contractors as they collect and analyze data.

Although EPRI owns and administers the test facility, others have roles that depend heavily on integrity and goodwill

The Inside Story

The role of the High-Sulfur Test Center is research and testing that can bridge the development gap from emission control concepts to proven designs that can confidently be extrapolated to commercial scale. This flexibility is symbolized by the intricately-connected ductwork among the major pilot systems and components. HSTC is designed to accommodate additional pilot equipment that may be needed for future research and test programs.



for success. Chuck Sjoberg, for example, is the Somerset plant superintendent, and Jim Cowe is NYSEG's site liaison. Both maintain interest in the HSTC test program, although their ultimate concern is the productivity of the $1 billion power plant itself.

HSTC has a steering committee, too, chaired by John Smigelski of NYSEG and made up of representatives from other sponsoring organizations. The committee holds what Dalton calls philosophical responsibility and provides rapid technology transfer from the facility. "It's interested in the plans, priorities, and directions of HSTC work." He distinguishes this from EPRI's fiduciary responsibility, as well as from its management responsibility, exercised by project managers and overseen by small ad hoc committees of utility advisers for each project.

Dalton and Glover and their steering committee hope that a number of utility employees can work at HSTC on a loaned basis. Since early this summer EPRI has been systematically canvassing its members for engineers to come to HSTC for one or two years. The appeal is rapid technology transfer, to be gained from hands-on experience with specific processes, and participation in test management.

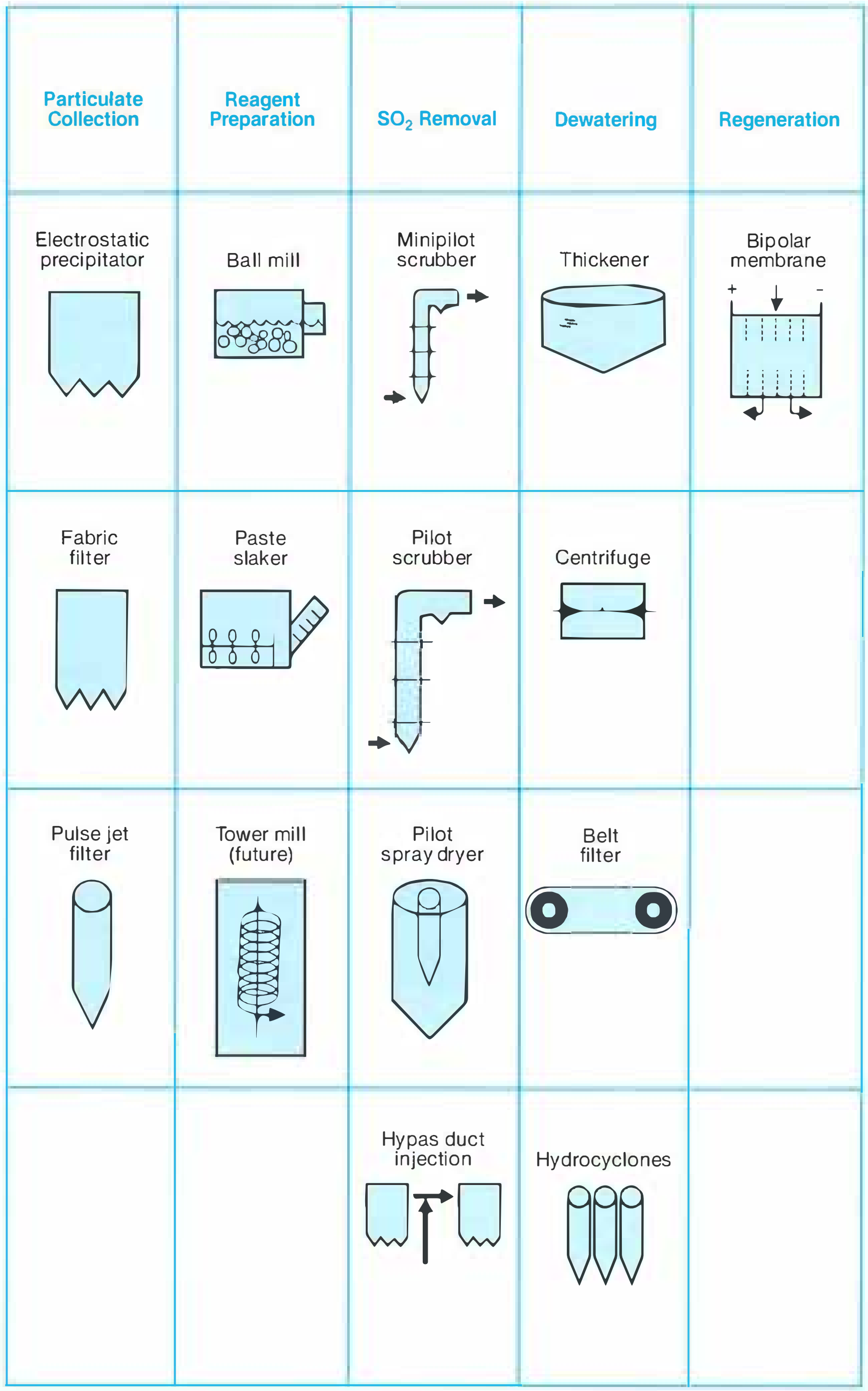
EPRI is prepared now to schedule assignments through 1996 and can accommodate two utility loanees at any time. Candidates are expected to come with a wide range of experience—from two to five years in design, operations, maintenance, or environmental testing. Dalton quickly ticks off the preferred technical disciplines, "chemical, mechanical, or environmental engineering, although," he adds, "there is always room for equivalent experience in other fields."

Five projects to start with

HSTC represents a projected 10-year investment of some $65 million. Design and construction cost a little more than $21 million. Operations and testing are each expected to cost about $2 million

Mix and Match

Subsystems can be matched in almost any combination to change emission control processes and alter their sequence. This flexibility also means adaptability to unforeseen needs and gives the dedicated HSTC an edge over separate pilot facilities.



annually through 1996, for a total of $40 million more.

EPRI has invested $21 million and plans to spend another $11 million. The five cosponsors to date have committed support ranging from $1 million to $5 million each, for a total of $12 million. Other organizations in the United States and abroad are showing interest in EPRI's request that they become cosponsors.

Five simultaneous test programs are now getting under way. The shortest of them will take at least three years, and others will fill out the initial five years of currently planned operation. New efforts will be phased in on a priority and space-available basis.

Wet flue gas desulfurization is still the largest single process category under development and test at HSTC. The continuing appeal is that wet FGD is known to have better than 90% sulfur removal efficiency. Accordingly, the next five years are fully blocked out with process model validation tests, crystallization studies, additive tests, research to cut maintenance needs and process energy use, efforts to downsize or eliminate components, and development of selected scrubbing processes.

The spray dryer is drawing strong interest because it probably can attain 90% efficiency and also because it costs less, the result of needing fewer expensive materials. In addition, it uses little water, thus requiring no extra heat for gas reheating. The spray dryer typically employs a slurry of calcium hydroxide that dries as it reacts with SO_2. The spent product is collected in the bottom of the spray tower and also at the particulate control, usually a fabric filter. Alternative reagents, additives, temperatures, and SO_2 concentrations will be varied in efforts to optimize sulfur removal, pressure drop, and reagent consumption.

Tests of scrubber reagents and their preparation in various mills are also planned during the coming three to five years. But schedules are being juggled to permit early and intensive work on two of the newly added processes.

One of these is the Hypas dry injection technology mentioned earlier. It and some other dry processes may reach the range of 50–80% sulfur removal efficiency. If environmental control standards are applied at less-stringent performance levels to plants now exempt, dry sorbent processes would be attractive as retrofit options.

The other newcomer is a regenerative scrubbing process with the trade name Soxal. It is a wet process, now planned for testing only at minipilot (0.4-MW) scale. Soxal features an electrodialysis cell with what is called a bipolar membrane. Applying a dc charge to the membrane separates the scrubber wastes, sodium-sulfur salts, into two compounds—a regenerated sodium reagent and a very concentrated SO_2 stream that can be converted to sulfuric acid, elemental sulfur, or gaseous SO_2 for other process uses.

Regenerative FGD processes have the potential for better than 95% sulfur removal efficiency. Also, they are what Dalton terms very tight packages, referring to their high level of integration—that is, minimal wastewater discharge and usable by-products.

Reliability the key

Percentage increments of efficiency are an important part of the progress sought in emission control development and testing at HSTC. Better efficiency addresses the strategic objectives of clean coal use in new plants and cost-effective emission reductions in older existing plants that might be targeted by acid rain legislation. Such improvements hack away steadily at the environmental risk associated with electric utility operations.

But when it comes to cost reduction, Dalton tends to emphasize the potential effects of better process and equipment reliability. "A more reliable FGD technology would allow you to have fewer spare absorber modules," he says. "If you need only three modules where now you need four, that's a 25% saving in module costs."

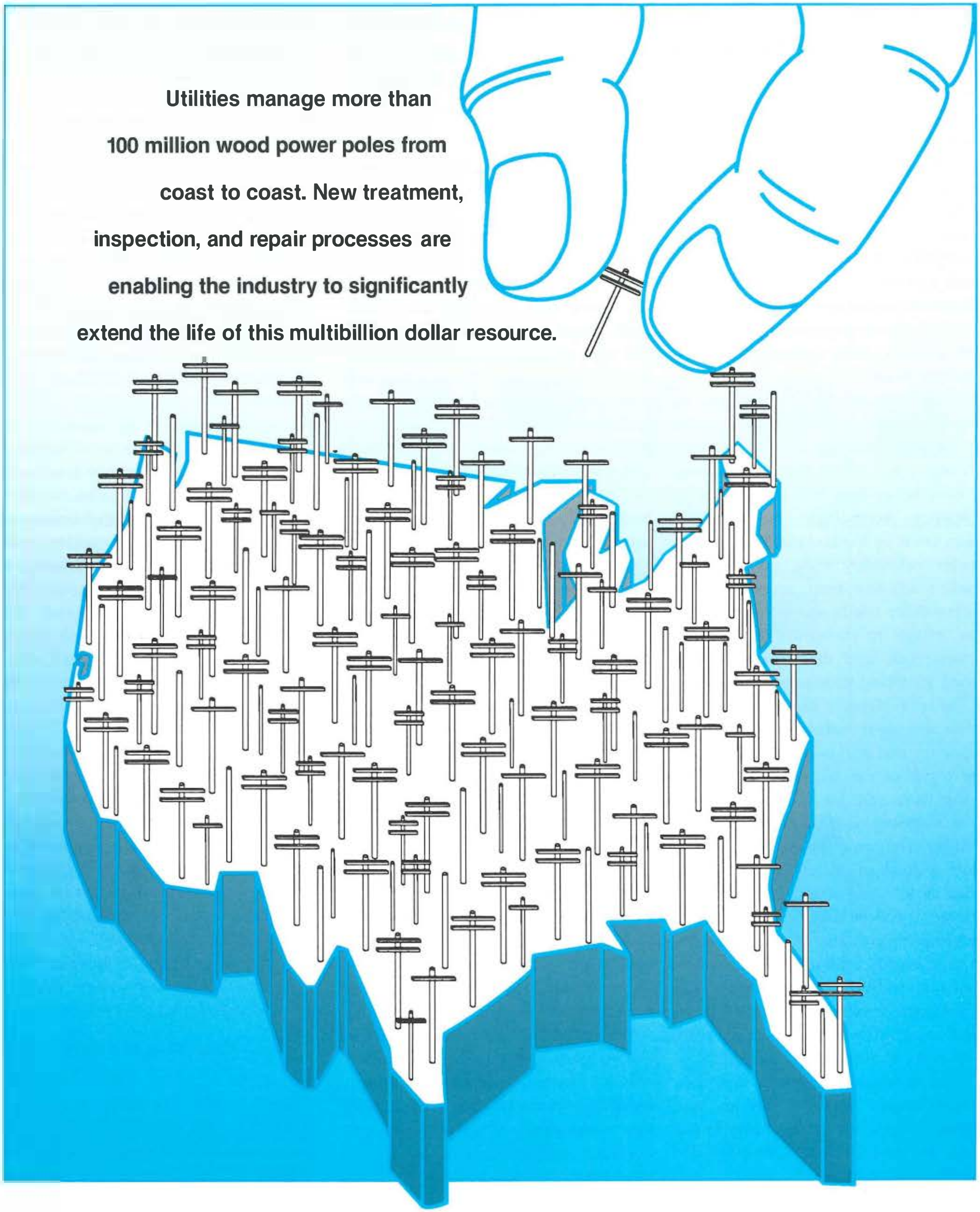
Continuing the train of thought, he suggests that a more reliable system, less likely to malfunction, would not have to be modular. Some subsystems could be larger, affording economies of scale.

Dalton also points out that spray dryer and dry scrubbing processes do not harbor wet, corrosive environments; this suggests that expensive, exotic materials would not be needed. "Not only that, but dry systems don't have to sacrifice energy for reheating the fuel gas. Those are direct sources of cost savings."

High-sulfur coal continues to be a key fuel for many utilities. If it is to be used responsibly, cleaner and more cost-effective ways to burn it are needed. The High-Sulfur Test Center is taking dead aim on the reliability of newly developed emission control processes and equipment. It provides a realistic environment for proving them at manageable, economical scale. HSTC results should go a long way in building confidence and dispelling uncertainty, two subjective but inevitably influential factors in the cost of new technology and the speed with which utilities adopt it. ■

This article was written by Ralph Whitaker. Technical background information was provided by Stuart Dalton, Coal Combustion Systems Division.

Utilities manage more than 100 million wood power poles from coast to coast. New treatment, inspection, and repair processes are enabling the industry to significantly extend the life of this multibillion dollar resource.



Managing America's Wood Pole Inventory

Imagine 100 million or so wood poles—many billions of dollars' worth—dotting the American landscape, strung together with power lines. Now keep an eye on each of them, from city streets to rural lanes and remote mountain passes. Track their aging and decay, and replace or repair them before they get too weak to do their job. Sound like a tall order? It is, but that's exactly what electric utilities have to do in maintaining a safe and reliable power delivery network.

After years of managing their poles with tried and relatively true techniques, however, utilities are making some changes. New wood preservatives are being developed in response to concerns that traditional treatments may pose health and environmental risks. New ways of extending the life of poles are evolving, from fumigant treatments that arrest internal decay to quicker, cheaper, and more visually attractive groundline repair techniques. Utilities are also, for the first time, building a base of diagnostic and design data on wood poles. Researchers have deliberately snapped more than 1000 distribution and transmission poles of all ages in the laboratory to measure how strong the poles really are and how rapidly they weaken under various climatic and service conditions. And a newly developed nondestructive evaluation tool offers a significant breakthrough by enabling field crews to actually measure the strength of in-service poles, rather than judging on the basis of visual inspection.

Safer preservatives for new poles

Utilities use from one to three million new poles yearly in new installations and as replacements for failed poles. Roughly 75% of the new poles are southern yellow pine grown in the Southeast; the remainder are Douglas fir or western red cedar from the Pacific Northwest. To protect against decay caused by insects, fungi, and bacteria, manufacturers routinely treat the poles with preservatives. The three most commonly used formulations are pentachlorophenol (Penta), creosote, and chromated-copper arsenates (CCAs). About 65% of the new poles are treated with Penta, 28% with creosote, and 6% with CCAs.

Several methods are used to treat poles—which range from 40 feet long and a foot in diameter at the base for distribution to twice that length and 2 feet in diameter for transmission service. Most techniques place the poles under vacuum in a treatment chamber to remove gases and moisture from the wood. The chamber is then flooded with a liquid preservative solution. In some cases the preservative is heated up to 180°F, and pressure is applied up to 150 psi to drive the preservative into the wood pores.

The traditional preservatives work quite well, keeping many poles in service for 30 years or more. However, their future availability is uncertain because the Environmental Protection Agency (EPA) has ruled them to be harmful and has restricted their use. The recent banning of Penta throughout Scandinavia and in Japan and West Germany could be a harbinger of future regulatory developments in the United States.

When EPA began considering regulations on the principal wood preservatives in the late 1970s, EPRI funded Michigan Technological University to develop and test safer, less-toxic chemicals for preserving wood poles. The researchers tested dozens of compounds in the laboratory, in fungus cellars (rooms where humidity and temperature are maintained at optimal levels for fungal growth), and in field tests in which 18-inch-long stakes were treated, placed in the ground, and evaluated for decay each year.

The effort identified two effective products. Alkylammonium compounds (AACs), which historically had formed the basis of some hospital disinfectants, were found to be an effective preservative for wood that is not in contact with the ground. Ammoniacal copper carboxylates (ACCs) were found to work well on wood in ground contact.

According to William Shula, the EPRI program manager overseeing the wood preservative research, "The work at Michigan showed that these two materials can compete with traditional preservatives in both cost and performance." To reach commercial acceptance, however, any compounds proposed for wood treatment must be accepted by the American Wood Preservers Association (AWPA) and be registered with EPA. Both AAC and ACC have been submitted for AWPA acceptance, but neither chemical has yet been submitted to EPA for review. Given the typical pace of such proceedings, it could be several years before the compounds are approved and commercially available for use on utility poles. "There will be a lot of interest in these alternatives if EPA tightens the regulations on Penta, creosote, and CCA," says Shula.

The new products are attractive because they are cost-competitive with existing preservatives and are expected to prove safer and more environmentally acceptable. Because they are waterborne, however, they have the disadvantage of making the exterior shell of the pole harder and thus more difficult to climb than oil-treated poles. "In addition," says Darrel Nicholas, a professor of wood research formerly at Michigan Tech and now at Mississippi State University, "some preservatives disperse too fast and thus don't act as long as oil-borne preservatives if they are delivered in a water solution. The carrier itself (water or oil) has a lot to do with the efficacy of the compounds and the service life of the treated wood."

Because some preservatives work better if delivered in solution with oil and because oil treatment leaves the wood softer and easier to climb, EPRI is funding Nicholas and his colleagues at Mississippi State to formulate and test new oil-based wood preservatives, using some of the active ingredients demonstrated in the work at Michigan Tech. This research has just begun, and it will be six years before field tests provide any conclusive results.

Extending pole life

Because it costs $1000–$4000 to replace a pole, utilities want to extend the safe service life of existing poles for as long as possible. Although the initial preservative treatment protects the outer portion of new poles, it does little to protect the untreated heartwood from decay-causing insects and fungi that penetrate through cracks that form naturally as the poles dry over the years. Internal decay is difficult to detect, but it can reduce a pole's life to as little as five years by spreading from the heartwood toward the outer shell of sapwood. The sapwood gives the pole 90% of its strength.

In the late 1960s researchers at Oregon State University began searching for treatments that would arrest internal fungal decay in the western red cedar and Douglas fir poles most prevalent on the Pacific coast. Funded initially by a group of western utilities and later by EPRI, the OSU team tested a number of agricultural fumigants used by farmers to control soil fungi. Two of these fumigants—Vapam and chloropicrin—were found to be particularly effective in controlling brown rot and white rot fungi that commonly invade and weaken the poles roughly 18 inches below groundline. Fungi typically thrive in this zone because of an ideal combination of oxygen and moisture.

The liquid fumigant is poured through holes drilled into the pole, typically near the groundline. The holes are then plugged with preservative-treated dowels, and the fumigant vaporizes and moves as a gas throughout a zone several feet above and below the point where it was applied. The OSU research showed that Vapam would halt fungal decay in Douglas fir and western red cedar for 8–12 years with a single treatment. Repeated treatments at 8-year intervals could potentially double or triple pole life.

Encouraged by the success of the research on cedar and fir poles, EPRI funded a follow-on project with the State University of New York at Syracuse to study the control of internal decay in southern pine poles. Data from this work are still being gathered and analyzed, but it appears that pine poles treated with chloropicrin have shown no signs of fungal reinvasion after six years, whereas there has been some reinvasion in Vapam-treated poles. "We need a few more years of study to reach any firm conclusions," says Shula, "but so far it looks like chloropicrin is working as well on southern pine as Vapam does on Douglas fir—and that's encouraging."

Utilities aren't waiting for final test results to act. Many of them have incorporated fumigant treatments into their pole management programs. Shula estimates that the industry is now treating about a million poles each year with fumigants. The Bonneville Power Administration estimates that the fumigant program is saving them $1500 per pole for 10 years in deferred pole replacement costs.

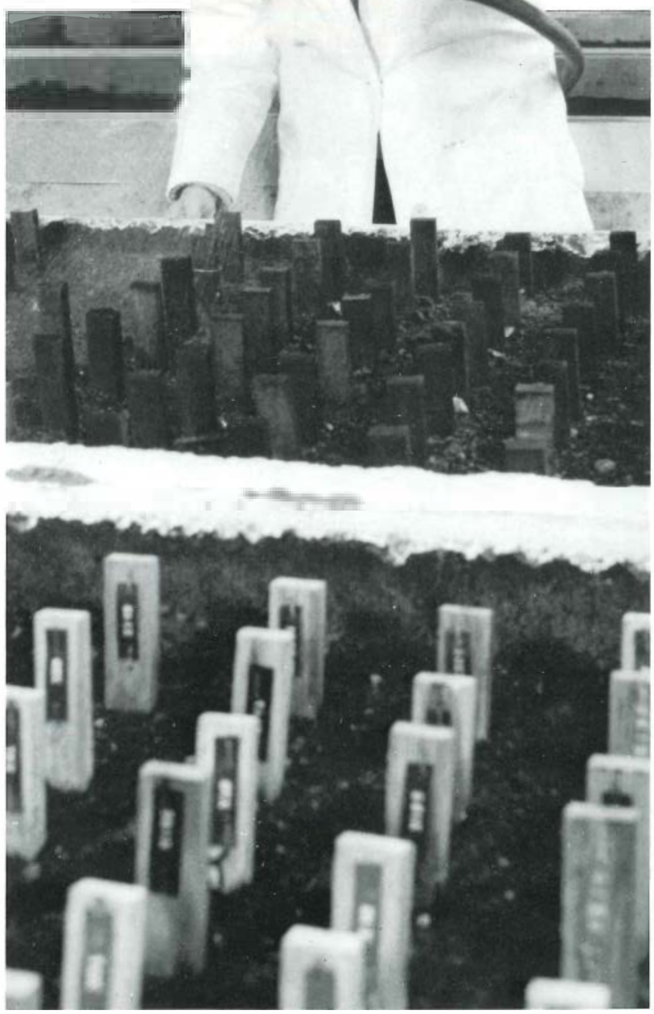
Although the eight or more years of protection offered by the fumigants is valuable, utilities would like to extend the preservatives' effectiveness over even greater periods. Toward this end EPRI is expecting to fund soon the development of slow-release, encapsulated fumigants.

As with time-release cold remedies, such an approach enables one treatment to provide a constant, low-level chemical dose over a much longer period than conventional treatments. EPRI Project Manager Harry Ng points out, however, that encapsulation offers more than longer treatment. "In addition to extending the protection offered by one treatment, slow-release encapsulation will

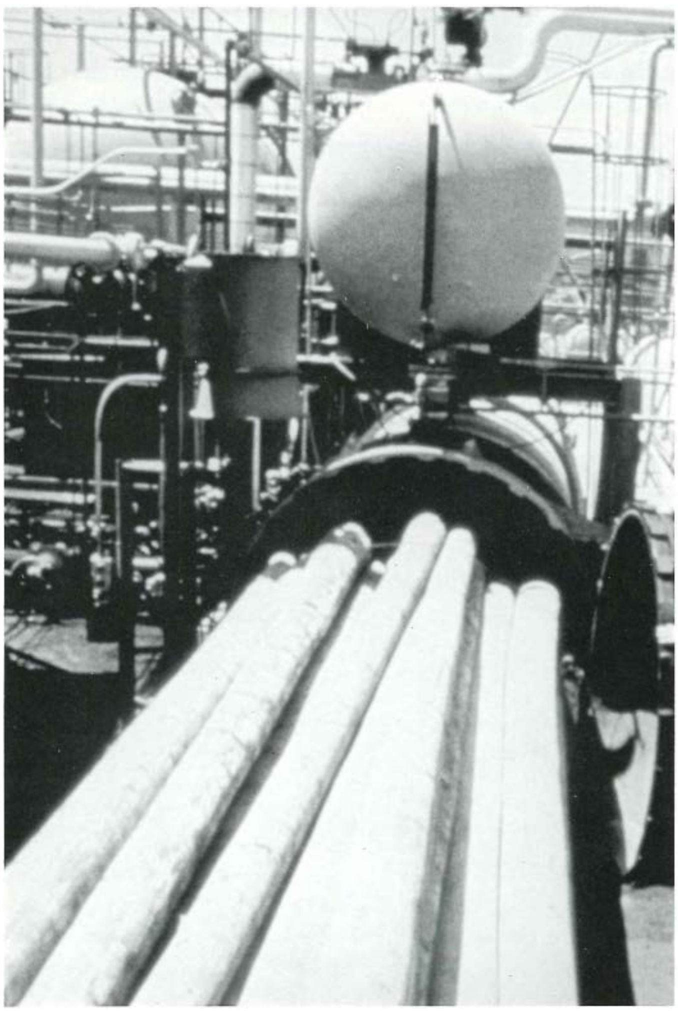
Initial Treatment

The one to three million new utility poles put into service each year are treated with pentachlorophenol (65%), creosote (28%), or chromated-copper arsenate (6%) to fend off fungal decay. EPRI is supporting development and testing of new preservatives for this initial pole treatment because Penta and creosote are under environmental review and could be more strictly regulated in the future. Two effective alternatives identified so far—alkylammonium compounds and ammoniacal copper carboxylates—are being tested on wooden stakes placed in the field and in laboratory settings kept moist and warm to encourage the growth of fungi.

Stake tests



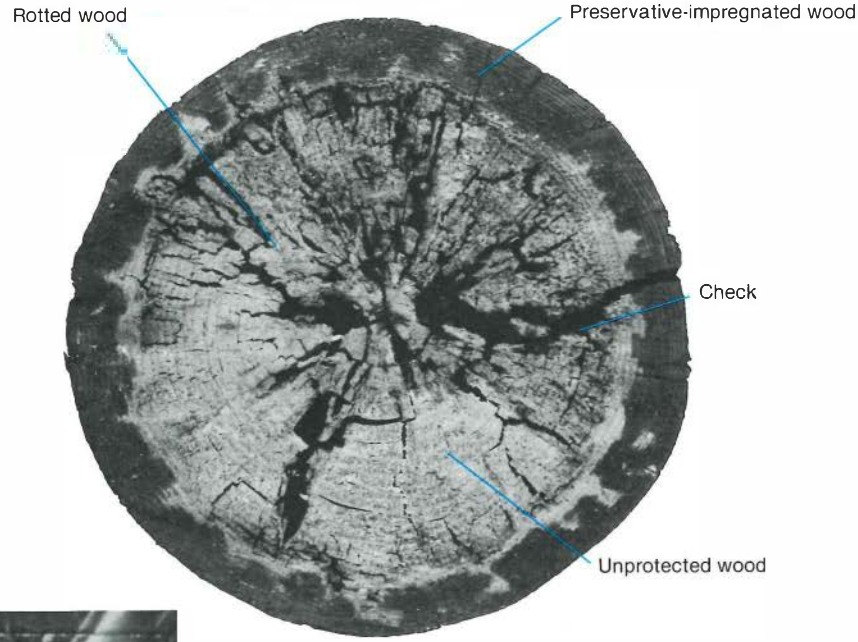
Utility poles being loaded for treatment



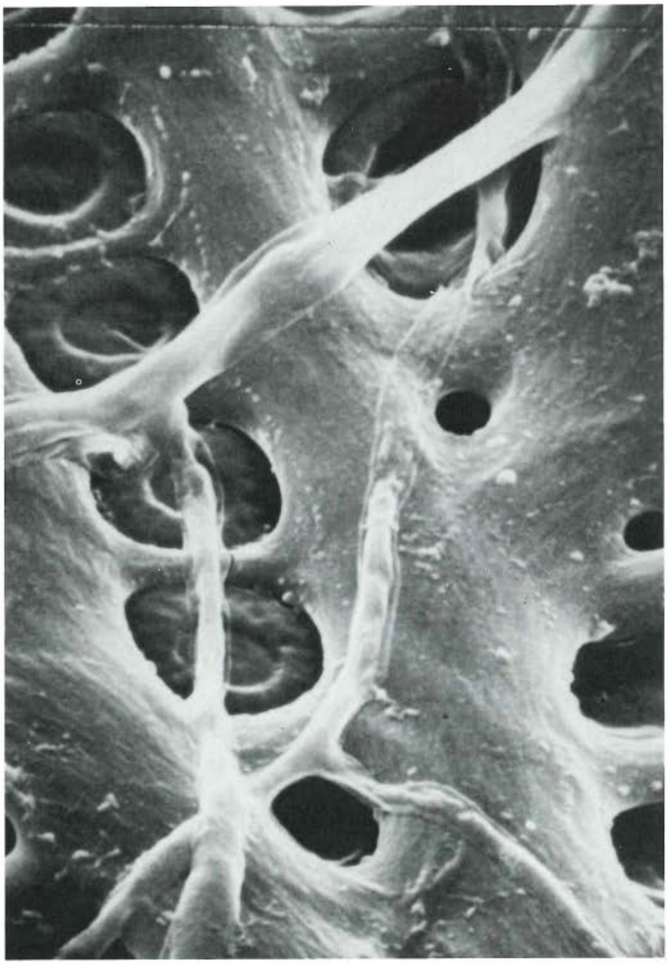
Decay and Re-treatment

Poles dry out as they age, forming vertical cracks called checks. These checks offer fungi easy entry to the heartwood, which is generally not penetrated by the original protection treatment. Here the fungi feed on the wood fibers and cause rot. To protect against this threat, new fungicide applications are being developed for periodic re-treatment of standing poles. Applied as a liquid through holes bored into the heartwood, the fungicides vaporize and inhibit fungal growth in the critical area several feet above and below groundline. Repeated treatments at intervals could extend average pole life from 20 or 30 years to more than 50 years.

Cross section of rotted pole



Fungal hyphae invading wood



Applying fungicide

make the fumigant easier and safer to handle, it will reduce potential environmental hazards by maintaining lower concentrations of active ingredients, and it will dramatically reduce retreatment costs."

In addition to attacks from fungi and insects, utility poles in many regions of the country are riddled with weakening holes drilled by woodpeckers seeking food or carving out nesting sites. In the spring of 1985 a pileated woodpecker blacked out service to 170,000 customers of Tampa Electric by poking too large a nesting space in a 22-inch-diameter transmission pole and sending it crashing to the ground. In most cases utility linemen find and repair woodpecker holes before they become dangerously large, but such vigilance costs money. Many utilities spend upward of $100,000 each year replacing and repairing woodpecker-damaged poles.

Southwest Research Institute has developed a woodpecker-repellent chemical that will keep the birds away for a season or two when brushed on the outside of the pole. With all the poles that utilities have to maintain, however, painting each pole with repellent even every other year would be too expensive.

In an attempt to bring the costs down, EPRI contracted with Southwest Research Institute to investigate the effectiveness of embedding its repellent more deeply into the wood of utility poles so that one application will keep the birds away for a number of years. To make accurate comparisons, the researchers will set up three kinds of composite poles to see how they fare in a woodpecker aviary. Composite poles were selected because it is relatively easy to embed the repellent in them. The first kind will be untreated composite poles; the second will be composite poles with the repellent brushed on the outside; and the third will be composite poles made out of wood chips that were pretreated with repellent. Because the chemical will completely permeate the last class of poles, researchers hope that it will fend off the birds for a number of years. If this technique proves successful, EPRI hopes to support an effort to find ways of embedding the repellent in solid wood poles.

Better repair techniques

No matter how effective pole preservation techniques become, virtually all poles will eventually weaken to the degree that they can no longer safely stay in service. Because fungi grow best in the moist wood just below the groundline, this is typically the weakest area in aged poles. When field inspections reveal significant rotting near the groundline, utilities must either replace the pole or reinforce the weakened section.

Until recently the most common reinforcement technique involved fastening the deteriorated pole to a wood stub anchored in the ground beside it and extending about 10 feet above the surface. Such repairs are somewhat unsightly, however, and have prompted customer complaints, so utilities have long sought an alternative approach.

With this need in mind EPRI funded the development of a new groundline repair technique. The result (now licensed by EPRI to three commercial firms under the brand names Nu-pole, Repol, and PoleGuard) involves screwing a split metal sleeve into the ground around the base of the pole and filling the space between the pole and the sleeve with aggregate and resin. Once the resin hardens, the reinforced section is stronger than the rest of the pole, making years of added service possible.

An economic analysis performed by Arizona Public Service concluded that the utility would save an average of $1400 per pole by using the Nu-pole system compared with pole replacement, while extending the average life of their poles from 30 or 35 years to 50 years or more.

The three commercial systems have been used in pilot programs by 12 major utilities since the marketing effort started less than three years ago. These pilot programs are repairing approximately 4000 poles per year for an annual saving approaching $4 million. According to EPRI Program Manager Richard Kennon, "As the technology becomes more widely adopted, we expect it to save the industry more than $100 million per year."

Diagnostics and data

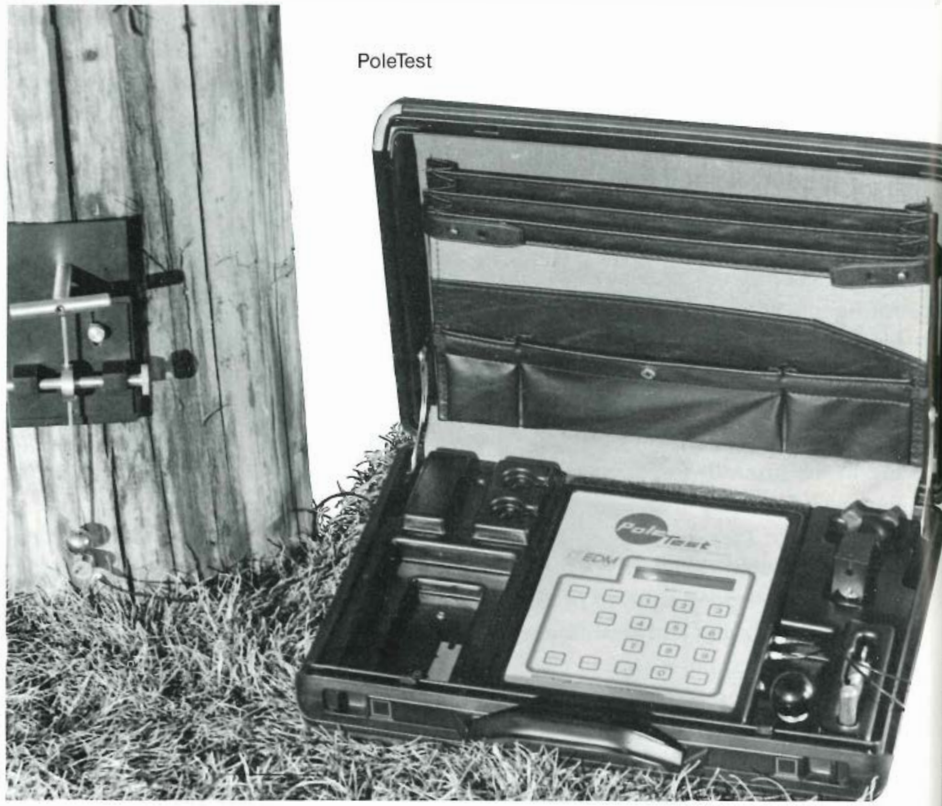
All these new developments in pole protection and repair are part of an overall effort to give utilities the tools they need to better manage their multibillion dollar pole resource. One of the most critical weaknesses in pole management until now has been a lack of data on pole strength and longevity.

The most prevalent method for evaluating whether a given pole is fit for continued service is to dig away the soil around the base and inspect the wood for visible exterior decay. In some cases field inspectors will drill into the pole or take core samples to check for interior decay. Another popular technique is to rap on the pole with a hammer and listen with a trained ear to judge the pole's soundness. Although an experienced inspector using these methods can draw some qualitative conclusions about the pole's integrity and the rate at which it is likely to deteriorate in the coming years, these subjective measures offer no concrete information on how strong the pole actually is.

To help give utility managers a better understanding of pole properties, EPRI funded Colorado State University and EDM Inc. to gather extensive data on more than 1000 transmission and distribution poles and then to measure their strength by placing calibrated loads on them until they broke. The data obtained in this 9-year testing program created for the first time a comprehensive picture of the range of utility pole strength for different species, in different service conditions over 30 years of service. (Some poles were new, others were used poles

Inspection, Diagnostics, and Data

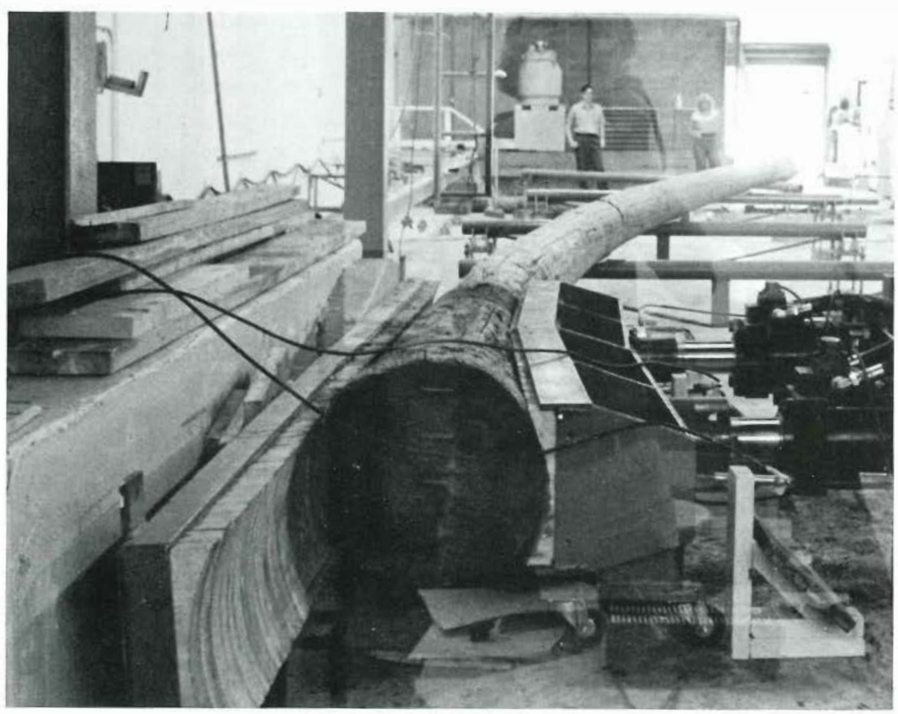
All poles ultimately reach a point where they are no longer strong enough to safely remain in service, but until recently, utilities had no way of accurately measuring the strength of in-service poles. To help utilities predict how quickly poles are likely to weaken under particular conditions, EPRI supported destructive testing of more than 1000 poles of varying ages and species and developed a pole strength data base from the results. These data are also incorporated in a device, called PoleTest, that enables field personnel to quickly and accurately measure a pole's strength on-site by analyzing its sonic properties with a portable microprocessor. If a pole is discovered to be weak at the groundline, its service life may still be extended for 10 or more years with an EPRI-developed repair technique that has been enjoying commercial success for several years. This process involves screwing a split metal sleeve into the ground around the pole and filling the gap with aggregate and resin, which hardens to a greater strength than the original wood.



PoleTest

Groundline repair

Destructive testing



of varying ages donated by utilities.)

Utilities can now draw on this data base to predict how quickly poles of certain species are likely to weaken in their climatic zone. They can then use these insights to optimize their pole inspection, maintenance, and field treatment schedules.

Nondestructive testing

The most important product to come out of the pole strength testing, however, was not the data base but a device that allows field crews to quickly and inexpensively measure the strength of individual poles. Developed by EDM under license from EPRI, the device is called PoleTest. The briefcase-size unit weighs about 15 pounds and is designed for portable field use.

The operator keys in the species and diameter and strikes the pole a few times with a marble-size steel ball mounted on the end of a three-inch pendulum. A built-in microprocessor analyzes the sonic wave patterns passing through the wood and correlates them with readings taken on similar poles in the destructive testing program. Within seconds, the microprocessor calculates the tensile strength of the pole to within 600 psi.

PoleTest opens up a whole new range of possibilities in wood pole management," says Jim Goodman, president of EDM. "Coupled with current inspection procedures it allows for much more accurate field inspection of in-service poles. It tells the utility engineer, for instance, whether an existing structure can bear the added load from a line upgrade or whether it is too weak for the conductors it now supports. Under the old methods, poles were sometimes removed from service when they were actually strong enough for more years of service. And conversely, some poles that were dangerously weakened were left in service because they appeared sound."

Patrick Hasenoehrl, a transmission standards engineer with Idaho Power, confirms Goodman's claim. "In 1986 we used the PoleTest prototype to run nondestructive evaluations along with conventional inspections on 1200 poles. Our conventional inspection identified 75 poles as rejects. NDE indicated that 29 of those 75 poles were strong enough to remain in service. By postponing the replacement of those 29 poles on one line, NDE saved us $100,000. In addition, PoleTest identified 3 poles that had passed visual inspection but were actually too weak to stay in service. It's hard to put a dollar value on that kind of information, but it's very important for avoiding costly pole failures and potential outages."

Tampa Electric reached similar conclusions about the accuracy of its conventional inspections. It submitted 24 poles that had been rejected and 25 that had passed conventional inspection to destructive testing. The tests revealed that about half of the rejected poles were strong enough to have remained in service and that about 30% of those that passed should have been rejected. Recognizing the capacity of the NDE technique to improve the accuracy of the existing inspection program, the utility incorporated PoleTest into its pole management program.

Hasenoehrl doesn't advocate throwing out the old techniques now that NDE is available. "Core borings, visual inspection, and microprocessor-based strength analysis are complementary techniques," he stresses, "and they should be used together."

Word about PoleTest is spreading quickly. It came on the market in mid-January, and as of mid-July, Goodman says he has more than 20 users, with inquiries building steadily. In addition to Idaho Power and Tampa Electric, early adopters of the NDE technology include Arizona Public Service, Omaha Public Power, Duke Power, Northeast Utilities, Central Louisiana Electric and Gas, and Pacific Gas and Electric.

It has been a busy decade in wood pole research, and the potential payoff totals billions of dollars in life extension and streamlined maintenance. Fumigants will reduce the decay rate, better groundline repair will extend the life of weakened poles, and more-comprehensive data will enable utilities to manage their pole resources more effectively and at lower cost. And if Penta, creosote, and CCAs are banned or severely restricted, the new generation of preservatives that EPRI has helped to develop will be ready to step into the market. Although some of these developments may seem somewhat mundane to those not involved in wood pole management, those close to the field are excited by the progress that has been made. For an industry that has more than 100 million poles to maintain, these improvements add up to major savings. ■

Further reading

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William Hayes. "Extending Wood Pole Life: Solving a $5 Billion/Year Problem." *Electrical World*, Vol. 200, No. 2 (February 1986), pp. 41–47.

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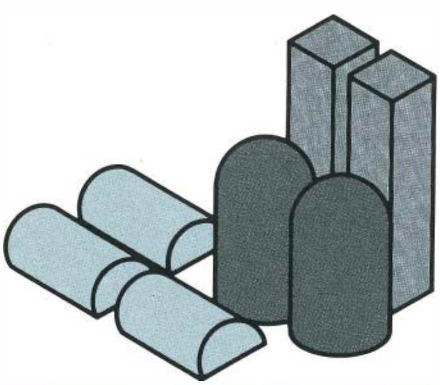
This article was written by Michael Shepard. Technical background information was provided by Richard Kennon, Harry Ng, and William Shula, Electrical Systems Division.

TECH TRANSFER NEWS

Pepco Plans GCC Capacity

Potomac Electric Power has announced plans for phased construction of a 750-MW-capacity coal gasification–combined-cycle (GCC) generating plant at its existing Dickerson station in Montgomery County, Maryland. To begin the state licensing process, the utility recently asked the commission to approve the siting of this facility at Dickerson.

The new two-unit plant would be the largest utility installation of GCC generation. The utility based its plans on the highly successful 100-MW Cool Water GCC demonstration plant in southern California. EPRI, as a major participant in the Cool Water program, assisted Pepco in the conceptual design.



Phased construction of the project (beginning in 1994) will involve the installation of combustion turbines that burn natural gas or oil; the later addition of steam bottoming cycles; and the eventual conversion to coal gasification, depending on fossil fuel prices in the late 1990s.

Present plans call for two GCC units. Each 375-MW unit will comprise two 125-MW combustion turbines, with 125-MW steam turbines added for combined-cycle operation as electricity demand increases.

According to Edward F. Mitchell, Pepco's president, the utility chose GCC technology because "it offers superior economic and environmental performance, and flexibility in choice of fuels." The utility, serving the District of Columbia and suburban Maryland, said the proposed expansion will range from $285 million to $1.3 billion in constant dollars, depending on the number of components brought on-line. ■ *EPRI Contact: Michael Gluckman (415) 855-2493*

TIP Research Categories Refined

Beginning with material mailed in mid September, new research categories will be used for EPRI's demand-driven Technical Interest Profile (TIP) system. These categories will more closely mirror the current areas of research. The TIP system is structured to enable EPRI members and other participants to receive one-page documents in their areas of interest. Documents distributed through this system include the Results series (Ready Now, First Use, and Off the Shelf), Events, Announcing, Host Utility, and the Report Summary.

Updating the research categories will give the individual participating in the system a better idea of the areas covered by EPRI research and will also allow EPRI to more accurately categorize the documents being distributed. ■ *EPRI Contact: The Hotline (415) 855-2411*

ADEPT Licensed in Europe

Several overseas organizations have recently licensed the Institute's ADEPT code, a software package to assist decision makers who deal with technical uncertainties involved in making broad policy decisions. The European Economic Community (EEC) is the newest licensee. The International Institute for Applied Systems Analysis in Laxenburg, Austria, became a licensee last November, joining the United Kingdom's Central Electricity Generating Board (CEGB), which has been using the code for several years under a similar licensing agreement.

These licensees will keep EPRI informed about their use of the model, advise EPRI of desirable model expansions, and make available to the Institute any published reports on their research.

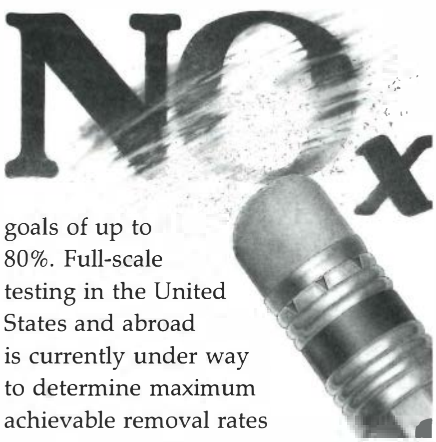
ADEPT is a versatile, open-program decision model to integrate and summarize what is known or not known about acid deposition in a given ecosystem. By organizing the unknowns in a decision analysis format, the model enables policymakers to consider widely different expert opinions in a meaningful way. Among these uncertainties is the question of how emissions might travel from source to receptor, which is of considerable interest in Europe, where emissions from one nation may be deposited in another.

Later this year a new version of ADEPT will offer still more detailed capability and will allow larger problems to be run on a personal computer. ■ *EPRI Contact: Richard Richels (415) 855-2602*

Urea Injection System Licensed for NO_x Control

EPRI has issued a license to Fuel Tech, Stamford, Connecticut, for a postcombustion NO_x control technology to be marketed under the trademark NO_xOut. Fuel Tech can also serve as EPRI's licensing agent for the process worldwide.

The NO_xOut process involves the injection of urea into the combustion gas path of fossil-fuel-fired steam generators to selectively reduce NO_x in the gas phase to molecular nitrogen and water. Fuel Tech will also add proprietary chemical enhancers to the urea to accommodate a broader range of injection temperatures and to improve overall NO_x removal. Potentially, the process can be retrofit to a wide range of coal-, gas-, and oil-fired boilers, with NO_x removal



goals of up to 80%. Full-scale testing in the United States and abroad is currently under way to determine maximum achievable removal rates under acceptable operating conditions.

To prepare United States utilities for the possibility of additional NO_x control requirements, EPRI sponsors research into both combustion modification and postcombustion technologies for NO_x control. "The commercialization of the postcombustion NO_xOut technology is another step toward EPRI's goal of providing the industry with flexibility and a variety of options to meet future requirements," says David Eskinazi, project manager in the Coal Combustion Systems Division. ■ *EPRI Contact: David Eskinazi (415) 855-2918*

CORRECTION In the June 1987 article on Tomcat, we reported that General Electric Canada had been awarded the contract to build a manipulator arm for the Challenger space program. That statement was incorrect: Spar Aerospace Limited of Toronto, Ontario, was awarded the contract to build manipulator arms for the entire NASA program. The government of Canada donated the first arm (built by Spar) to the American people.

Microcomputer System for Weibull Failure Analysis

Power plant components, such as boiler tubing systems, are subject to random failures, with each class of components showing typical failure patterns. To analyze failure data and discover these underlying patterns, utilities can use a new microcomputer-based software system that employs Weibull failure distribution statistics.

Development of the software began with a mainframe version that was first applied to analysis of battery systems. An EPRI report, *Weibull Failure Distribution Analysis and Plotting System* (EM-3658-CCM), describes the method and its first application. More recently, developers extended the code for use on personal computers and for large data samples of the kind needed to support systemwide analyses.

Utility personnel can use this interactive, menu-driven system to estimate failure characteristics of many different systems. The program takes component failure data as input and produces a graphic display and printed plot of predicted failure patterns. By using this information, utilities are able to structure maintenance testing and parts-replacement programs that will coincide more closely with the service life of components. At Duke Power, engineers are currently exploring applications of the microcomputer-based program to failure data from boiler tubing systems, pumps, and turbines. The program is currently available through the Electric Power Software Center. ■ *EPRI Contact: Robert Weaver (415) 855-8947*

Avoiding the Pitfalls of Small-Hydro Development

Because of the economic advantage suddenly afforded by hydroelectric power after the rise in oil prices in the 1970s, utilities and other organizations discovered a need for more information about the development of small-hydropower sites. Today these developers can turn to a new resource for practical advice on carrying out small-hydroelectric projects smoothly from beginning to end.

This new guide for developers, issued as Vol. 4 of *Small-Hydropower Development: The Process, Pitfalls, and Experience* (EPRI EM-4036), addresses government requirements and developmental procedures that have been crucial to the success of small-hydro projects. The topics covered include project planning, environmental considerations, the regulatory process, economic analysis, marketing and power sales, financing, project implementation, and general operation and maintenance procedures. The material is presented in a systematic format that can be instructive to both technical personnel and nontechnical developers.

The guide is the last volume of the report for a small-hydropower technology transfer project initiated by EPRI and DOE in 1982. The other volumes summarize and analyze 240 feasibility studies (Vol. 1), 41 license applications (Vol. 2), and the 17 completed construction projects (Vol. 3, forthcoming). ■ *EPRI Contact: Charles Sullivan (415) 855-8948*

Molten Carbonate Fuel Cells

by R. H. Goldstein, Advanced Power Systems Division

ABSTRACT *EPRI's advanced fuel cell technology subprogram has two objectives. The first is to reduce the cost and heat rate of the electric utility phosphoric acid fuel cell (PAFC) from the state-of-the-art value of 8300 Btu/kWh (natural gas to ac power) to levels that will be more competitive in the future (about 7500 Btu/kWh, or 45.5% efficiency). The second goal is to develop the molten carbonate fuel cell (MCFC), which should offer a lower system cost and lower heat rate. This report reviews recent progress in MCFC development.*

There has been a great surge of interest in the MCFC system outside the United States in the last several years. In particular, an initially small effort in Japan has grown considerably, and programs have begun in the Netherlands and Italy. One reason for this attention is the efficiency improvement the MCFC is projected to offer over the PAFC for such fuels as natural gas and gas derived from gasified coal. In addition, the MCFC potentially has less-stringent materials requirements, and certain MCFC variants will have a much simpler chemical engineering system than that of the PAFC. The MCFC's greater simplicity translates into a potentially lower capital cost than that of the PAFC, and both this and its greater potential for improved efficiency are likely to make it a more effective competitor to other advanced generators, such as a combined-cycle system operating on clean liquid or gaseous fuels.

The MCFC is expected to produce electric power from natural gas—and probably from other available clean hydrocarbon fuels (e.g., liquefied petroleum gas and light distillates)—at a higher-heating-value (HHV) efficiency of 50% or better, even in units as small as a few megawatts. It also produces waste heat at temperatures of about 1100°F (600°C), which could in turn be used for cogeneration or in a bottoming cycle to increase the HHV efficiency to 60% or higher. Emissions are expected to be very low; for example, NO_x concentrations of only about 1 ppm are expected, a result of the MCFC's chemistry and chemical engineering. In contrast, NO_x concentrations are about 5 ppm for the PAFC and about 20 ppm for the combined-cycle plant under the most favorable conditions. Hence the MCFC could be installed in smaller incremental units with better fuel economy than combined-cycle plants using the same fuels.

The MCFC is also a candidate for integration with coal gasifiers and steam or combustion turbine bottoming cycles. Design studies show that the MCFC can offer overall coal-ac efficiencies of about 50% with Texaco-type entrained-flow gasifiers like those being used in the Cool Water project. This is not necessarily the optimal gasifier approach—a less heat-intensive gasification system that produces some methane may be used advantageously with the MCFC (*EPRI Journal*, December 1984, p. 63). Coal-ac efficiencies of 55% may be possible; however, capital cost considerations, especially in the MCFC stack, may mean that the lowest-cost electricity would be produced at somewhat lower efficiencies.

MCFC development

U.S. work on the MCFC started in 1959 at Chicago's Institute of Gas Technology (IGT), where it has continued under successive American Gas Association (AGA), Energy Research and Development Administration, EPRI, and DOE funding. MCFC technology was selected as a backup to the PAFC by United Technologies Corp. (UTC) for the AGA's TARGET program for small cogeneration fuel cell units in 1967. In 1969 Energy Research Corp. (ERC) was founded, largely on the basis of IGT experience, and it has since continued MCFC development, most recently under DOE and EPRI funding. These three organizations—IGT, UTC, and ERC—now conduct most of the U.S. research on MCFC technology.

EPRI's funding has been insufficient to develop a practical MCFC stack; hence its efforts are closely coordinated with, and are dependent on, the DOE program. Starting in 1980, EPRI's plan was to develop designed-to-cost components and stacks at ERC (RP2344). Emphasis in the EPRI program has been on components for the eventual atmospheric-pressure, internal-reforming

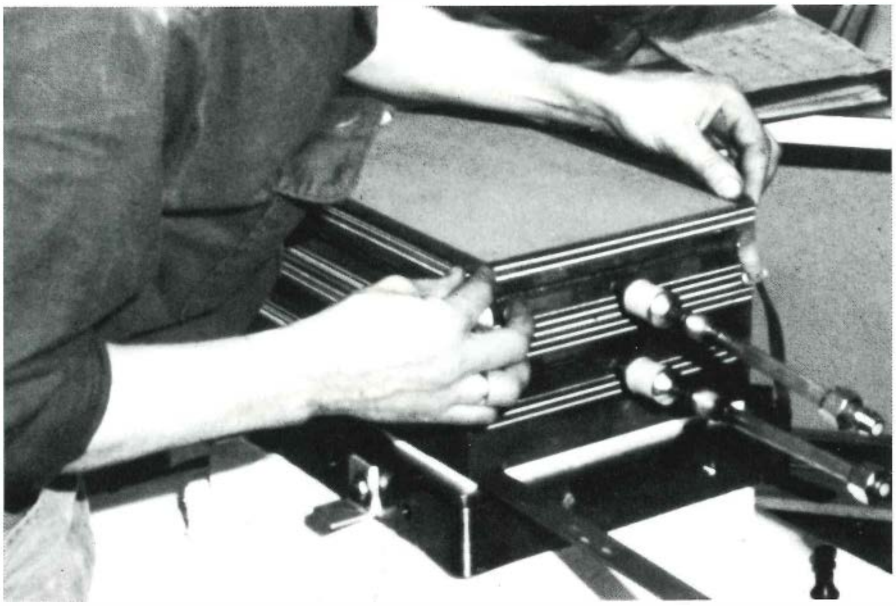
MCFC described in the December 1984 *EPRI Journal* report. Although DOE has supported ERC in the development of advanced cell components over this period, the main DOE emphasis is still on elevated-pressure stacks for use with coal gasifiers.

EPRI is also supporting an MCFC component development project at IGT, in which parallel approaches to those at ERC are being examined (RP1085-10). The major contributions of IGT's effort on cell components have been (1) to optimize the procedure for tape-casting the lithium aluminate layer for the electrolyte matrix, and (2) to develop new approaches to creep-free anode structures, particularly by using the pack-cementation method to incorporate dispersion-hardenable aluminum into nickel sinter structures and by examining other nickel-hardening agents. ERC's approach to this problem is to develop sintering methods for nickel alloy powders containing aluminum and other reactive metals.

ERC and IGT are developing improved internal-reforming concepts under DOE and EPRI funding, respectively. The primary effort focuses on the use of carbonate-resistant supports to prevent mechanical disruption of the reforming-catalyst structure. This carbonate attack can occur by means of the vapor phase or by electrolyte creepage caused by surface tension forces; electrolyte creepage is the more important mechanism under normal conditions.

ERC and IGT, therefore, have not only explored the use of the very stable lithium aluminate as a reforming-catalyst support but have also developed a porous carbonate barrier between the support and the anode. Because earlier DOE-supported work at General Electric showed that nickel was not wet by molten carbonate under reducing conditions, ERC uses porous nickel sheets for the barrier, while IGT turned to fine nickel sinters that allow gas to pass with little resistance. With its approach, ERC succeeded in operating an internal-reforming cell successfully for 7000 h. Such promising results provide confidence in the feasibility of the internal-reforming natural gas MCFC.

Figure 1 A prototype of the internal-reforming natural gas molten carbonate fuel cell, which has 10 cells and is about 1 ft^2 in size.



A small, 10-cell internal-reforming stack with a nominal area of 1 ft^2 (0.09 m^2) was operated recently in RP2344 (Figure 1). The stack's performance was the same whether natural gas was used directly or hydrogen and carbon dioxide synthesis gas was used (Figure 2).

MCFC stacks

Since General Electric voluntarily terminated MCFC work in 1984, DOE's primary stack development effort has been at UTC. In 1985, after work on a series of 1-ft^2 stacks successfully resolved the problem of electrolyte management experienced in early stacks, UTC began an effort to scale up components to 8 ft^2 (0.74 m^2). Confidence in the MCFC scale-up was raised by the greater than 5000-h operating life of the last 1-ft^2 20-cell stack. Operating life was determined by comparing electrolyte loss with the available inventory. Because there is evidence that relative loss depends on a stack's linear dimensions, the problem should be much easier to handle in large stacks. As of May 1987, the 8-ft^2 20-cell UTC stack had operated successfully for 1765 h.

The next stage in DOE's development program will be an effort, starting in FY87 and extending over five years, to design and demonstrate pressurized commercial-configuration stack components, short stacks, and, eventually, pressurized stacks of about 0.5–1 MW. The cost of this program is ex-

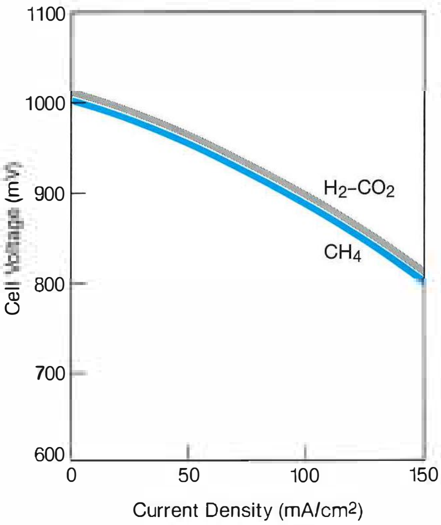


Figure 2 This graph illustrates the operation with natural gas (CH_4, color) and with synthesized reformate gas (H_2-CO_2, gray), indicating the performance of the stack did not change.

pected to be over $50 million. Meanwhile, a similar effort to develop two 1-MW systems has been proposed by the New Energy Development Organization (NEDO) in Japan. This will initially involve five developers (Toshiba, Hitachi, Fuji Electric, Mitsubishi Electric, and Ishikawajima-Harima Heavy Industries). The cost to the Japanese developers, exclusive of cost sharing, is expected to be $200 million over nine years. Each developer is taking a different technical approach, and all have now completed 10-kW stacks of intermediate component size.

Remaining MCFC problems

Cathode stability is now the principal materials problem. Suitable substitutes for nickel oxide, which slowly migrates to the anode, have not been found, but research continues at Ceramatec, Inc. (RP2278-7), Case Western Reserve University (RP2278-6), and Argonne National Laboratory (DOE).

Much progress has been made in resolving other developmental and materials problems—anode creep, electrolyte inventory, and reforming-catalyst contamination. None of these now appear to preclude achieving reasonable durability goals. Increasingly, emphasis can shift to engineering development of the fuel cell stack and the development of cost-effective manufacturing processes for its components.

Environmental Assessment

Risk Management of Gas Plant Waste Sites

by Victor Niemeyer, Environment Division

Manufactured-gas plant waste sites pose a problem of considerable importance and complexity. They may present significant health or environmental risks, but although there are hundreds or perhaps thousands of individual sites, little is known about them or the risks they may pose. Because only a few sites have been investigated, our general experience and understanding of them is limited.

For historical reasons, many sites are currently the responsibility of electric utilities. Collectively, electric utilities may face hundreds of millions of dollars in costs for site investigations, remedial actions, and legal settlements.

To help the utility industry manage the health, environmental, and economic risks from contaminated sites, such as those associated with manufactured-gas plant waste disposal, EPRI sponsored the development of the contaminated sites risk management model, SITES. This effort is an extension of EPRI research on solid-waste risk management (RP2595).

Several characteristics of gas plant sites suggest that the problem is of considerable difficulty and importance. Many coal tars and other gas plant wastes contain substances that are known to be harmful to humans and/or animals in relatively small doses. Although it is not reasonable to assume in advance that significant risks exist at a particular site, it is also not possible to conclude that the risks are negligible without explicit analysis of the potential effects.

Another difficulty is that the complexity of these sites makes it difficult to analyze the risks they pose and to choose effective risk management options. The wastes typically contain dozens of distinct compounds in varying concentrations. The waste materials may have dispersed over a relatively wide area, with numerous areas of high concentration, but because they are below the surface they are hard to find. Subsequent development on or adjacent to a site constrains and complicates site investigation and remedial action, and it also increases the potential for human exposure.

From a data management perspective, it is difficult to track the different wastes present at a site, their environmental fate, the potential human and ecologic effects, and the implications of these factors for choosing among the alternatives for remedial action at the site. And the sheer number of gas plant sites poses another major challenge.

Thus organizations with ownership of or responsibility for gas plant sites face a series of challenges. They must determine not only which sites merit attention but the degree of urgency. For the sites that are to receive attention, they must ascertain the amount of site investigation effort necessary and the direction of this effort. Having gained an improved understanding of a given site, the owners of the site must then decide whether remedial action is necessary. If it is, they must evaluate a set of options to identify the course of action with the optimal combination of risk reduction and cost-effectiveness.

These choices may be constrained by regulatory requirements but will inevitably necessitate addressing certain questions: How clean is clean enough? How much money should be spent toward restoration? Not only are these choices difficult, but it is essential the decision process be managed in such a way that the basis for the choices be clearly communicated within and outside the responsible organization.

The SITES system

EPRI's SITES system can help utilities quantify the risks at gas plant waste sites and choose cost-effective options for remediation where appropriate. The system is a decision support tool implemented in user-friendly software designed to run on IBM-compatible PCs. It is a flexible risk management model, based on the methodology of decision analysis. Decision trees are used to compare different site investigation and remedial action options, track alternative scenarios, and reflect uncertainties in key parameters.

The SITES software system is integrated in a single package that allows the user to easily input data, specify analyses, and interpret results. The system logically and conveniently links information on site contamination, transport and fate of contaminants, human and environmental exposure, health and environmental effects, and both direct (e.g., site investigation) and indirect (e.g., legal) economic costs.

As an integrating tool, SITES does not include a detailed model of each component of the problem but is designed to incorporate input from such models. Extensive work is under way at EPRI and elsewhere to develop models of the migration and off-site transport of both organic and inorganic substances. SITES is designed to be used in concert with such transport and fate models for each site situation, with the SITES system providing a consistent integrating framework for all analyses.

Although the development of SITES was originally motivated by concern over PCB contamination, the system is applicable to a broad range of site contamination problems. SITES was tested in two preliminary analyses of gas plant waste sites, which successfully demonstrated its applicability.

ABSTRACT *Gas manufactured from coal and oil was used widely in the nineteenth and early twentieth centuries, until the availability of less-expensive natural gas from interstate pipelines made this technology obsolete. The processes that were used to manufacture gas produced oily tars and sludges as by-products. These wastes contain polynuclear aromatic hydrocarbons, other hydrocarbon compounds, and a variety of trace metals and other substances. In many cases the wastes were buried or otherwise disposed of at the gas plant sites. The recent discovery of such wastes in a number of locations has led to concerns regarding environmental impacts and potential effects on human health. In turn, these concerns led to the requirement of remedial actions under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, or the Superfund) at a number of sites. Many more sites may be subject to action either under the Superfund or under state regulations.*

A SITES case study

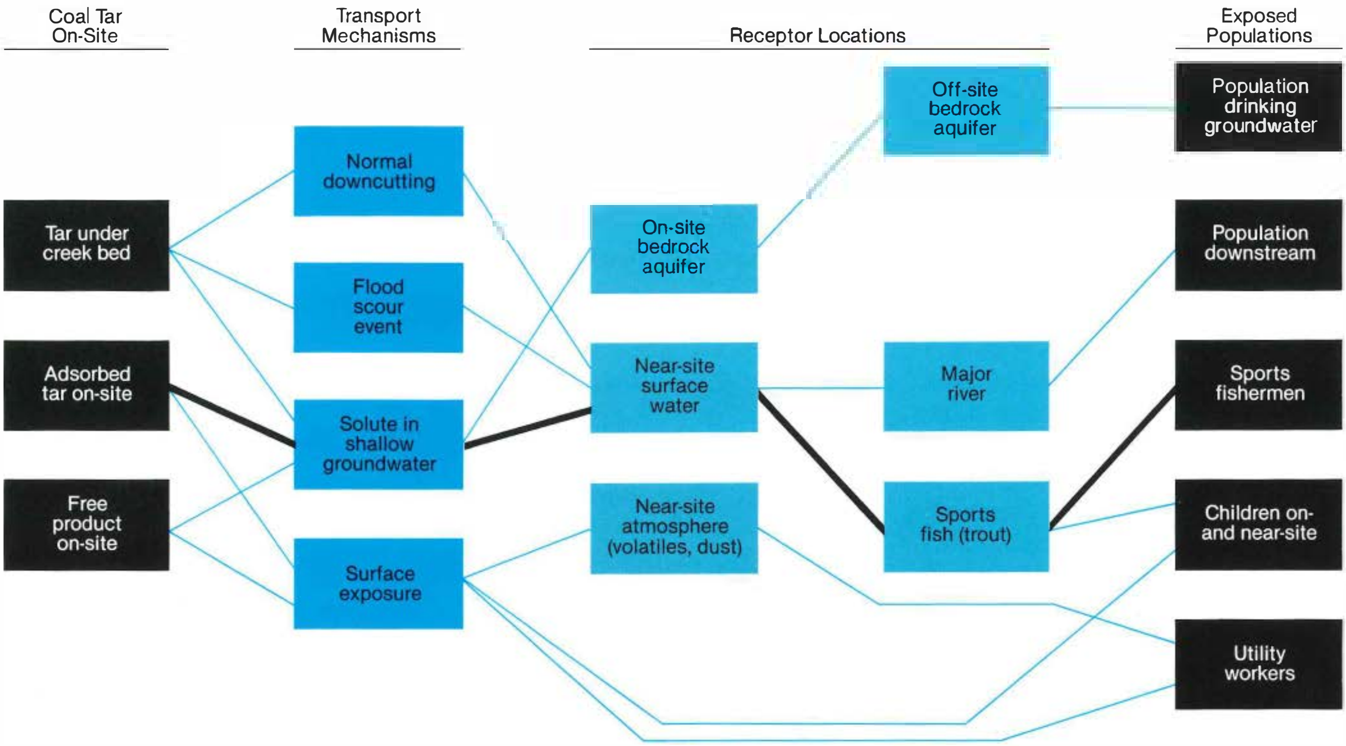
SITES was used recently in the analysis of a manufactured gas plant waste site near a small stream. An emergency cleanup several years ago had removed much of the coal tar at the site, and a partial slurry wall had been installed at that time to reduce migration of contaminated groundwater to the stream. The issue being addressed in the SITES analysis was whether additional remedial action was warranted. In its analysis, the utility sought answers to three questions.

- What are the health and environmental implications of remedial action alternatives?
- Which population groups, if any, face significant health risk from exposure to materials from the site?
- Does flooding near the site pose a significant pathway for risk?

SITES was used to evaluate three levels of remedial action: taking no further action beyond the initial cleanup; adding a full slurry wall and cap; and excavating and removing contaminated material to a landfill. The risk analysis was conducted for total polynuclear aromatic hydrocarbons, benzo-a-pyrene, metals, and phenols. Figure 1 charts the key pathways for exposure and the population groups at risk. The health effects considered included cancer and chronic noncancer health effects (such as loss of body weight, liver and kidney damage, jaundice, and eye disorders); the environmental effect considered was loss of sport fishing. The results showed that the cleanup several years ago had reduced the overall risk at the site by a factor of 55 and that further remediation would be of only marginal value. The dominant pathway for exposure was found to be ingestion of contaminated fish, with fishermen facing the greatest (although extremely small) individual risk. Flooding did not appear to be a significant source of additional risk.

The risk pathway structure of the SITES

Figure 1 **The SITES model helps the analyst track the multiple pathways linking toxic materials at a site with health and/or ecologic effects in potentially exposed populations. In this example three sources of coal tar at the site are linked through four transport mechanisms to different receptor locations and exposed populations. (The black leaders demonstrate the dominant pathway leading to potential health effects.) SITES estimates the risks associated with each pathway and how those risks are reduced by alternative remedial actions.**



analysis was useful in developing insights on further site investigation and remedial actions. Because the fish-fishermen pathway heavily dominates the others, investigations reducing uncertainty in this pathway have the greatest value in refining the analysis. Future efforts will be directed at sampling creek water and analyzing tissue samples from fish caught near the site. Remedial actions that discourage fishing near the site, such as fencing off the site or stocking fish in other locations, would be much more cost-effective in reducing the risk than the conventional remedial actions under consideration.

Because of the diversity of manufactured-gas plant waste sites, EPRI plans to continue testing the SITES software in additional case studies to provide additional examples of how the model can be used. Utilities interested in participating in these case studies should contact the EPRI project manager. The SITES software and a draft of the user's guide are currently available on a prerelease basis from the project manager, and the production version of the software will be available through the Electric Power Software Center this fall. Later in 1987 the first of the case study applications of SITES will be published to guide future users.

Water Management

Fish Protection at Cooling Water Intake Systems

by Wayne Micheletti, Coal Combustion Systems Division

Section 316 (b) of the federal Water Pollution Control Act requires utilities to minimize adverse environmental impacts in the operation of cooling water intakes by using the best available technology (BAT). Traditionally, physical barriers, such as traveling screens, have been accepted as the BAT standard. Entrained fish that impinge on these screens are usually removed with an automatic spray backwash and/or collected in special buckets or scoops for return to the source water through a sluiceway.

Concern has arisen, however, that fish handled in this manner may become stressed or weakened and may not survive after being returned to their habitat. In addition, under extreme circumstances fish can impinge on traveling screens so rapidly that they cannot be removed quickly enough to prevent the screens from collapsing. As a result the cooling system, and hence the plant, may have to be shut down.

An obvious approach to fish protection is to reduce impingement by limiting the number of fish that enter the area of the intake structure. An evaluation of intake technologies conducted for EPRI by Stone & Webster Engineering indicated that behavioral barriers offer a possible solution (CS-3644). Behavioral barriers rely on controlled stimuli, such as light and sound, to divert or attract fish. Because laboratory and field data for behavioral barriers were limited, EPRI and a group of cofunding utilities decided to conduct a series of one-year field tests in different source water environments.

Three types of behavioral barrier were selected for field testing: poppers (pneumatic air guns), air bubble curtains, and strobe lights (Figure 1, p. 46). The popper uses a solenoid valve actuated by a current pulse to produce a sound with high-pressure bursts of air at a frequency of approximately 50 Hz. The air bubble curtain is created by filling a diffuser hose with compressed air to generate bubbles about 0.06 inch (1.5 mm) in diameter or smaller. The strobe lights are standard xenon flashheads enclosed in watertight casings; an electronic controller sets the flash sequencing and rate (200 flashes per minute) at a light intensity of 4500 candelas.

These barriers were to be tested individually and in combinations for four cooling water sources (lake, river, estuary, and ocean) with widely differing aquatic species. The testing program is expected to extend over a four-year period. The devices will be tested for one year at each cooling water source. Lawler, Matusky & Skelly Engineers was retained to coordinate the field testing and to ensure collection of adequate and comparable data.

ABSTRACT *In the United States, electricity generation ranks second only to agriculture in requiring a large, dependable water supply. This water is used primarily for power plant cooling. Removing large volumes of water—as much as 500,000 gal/min (31.5 m^3/s) per megawatt for once-through systems—from the supply source can result in high mortality for local fish populations. Fish can become entrained in currents created by cooling water intake systems and subsequently may impinge on intake screens installed for debris removal. Since 1985 EPRI has been evaluating the use of behavioral barriers for reducing fish entrainment at intake systems. Results to date suggest that combinations of these barriers may limit the environmental impact of power plant water use.*

Site 1 testing

Ontario Hydro's Pickering nuclear generating station, on a freshwater lake, was selected as the first site. Because the Pickering station was a site for previous intake system research, funded by the Empire State Electric Energy Research Corp., control and experimental structures were already in place, and an extensive data base on seasonal fish populations was available.

The test facility is approximately 250 ft (76 m) offshore from the station's intake channel and consists of two identical structures—one for experimental testing and one for simultaneous control testing. Each structure contains pilings, on which gill nets and wing nets have been mounted. For the EPRI study, the pilings of the experimental structure were also fitted with poppers and strobe lights, as well as an air bubble curtain along the lake floor spanning the front opening.

A total of 142 paired control and experimental tests were conducted during two periods: July 1–August 23, 1985, and May 1–June 30, 1986. Tests were performed at two-hour intervals—primarily at night, when the fish were most active. At the end of each test, the gill and wing nets were raised and the collected fish were removed to a holding tank, where they were sized and counted. Data on current velocity and water temperature and turbidity were collected to determine whether these parameters had any influence on the performance of the behavioral barriers.

The effectiveness of each barrier or combination of barriers in diverting fish from the test structure was calculated on the basis of the difference between the numbers of fish caught in the control and the experimental structures and was expressed as a percentage.

The results had to be adjusted after paired control tests (tests with no barriers operating on either structure) showed significant differences (as high as 38%) between the numbers of fish collected in the

Figure 1 Three behavioral barriers being tested in this project: (top) strobe light; (middle) popper; (bottom) air bubble curtain.

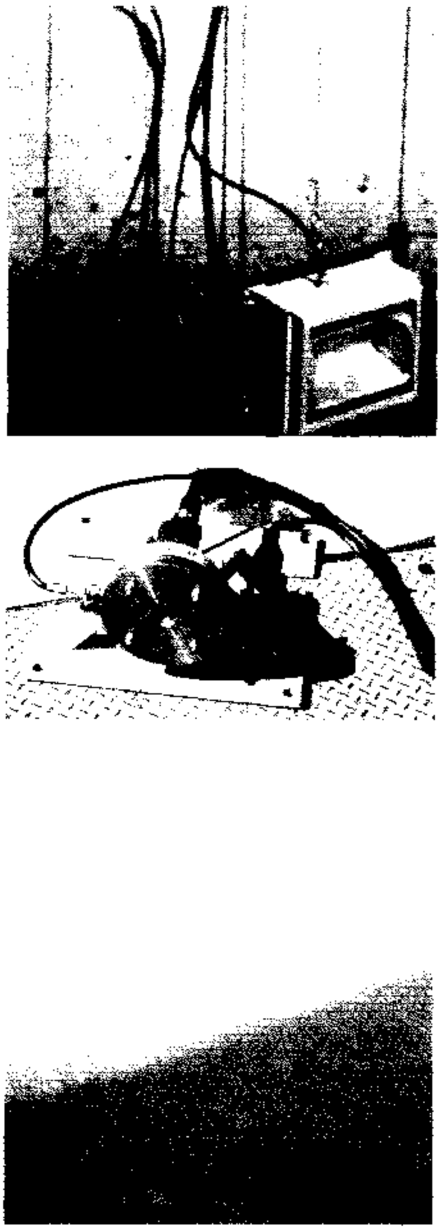


Table 1
EFFECTIVENESS OF BEHAVIORAL BARRIERS
(Site 1 field test results—%)

Barrier	1985	1986
Popper	73	78
Air bubble curtain	−13	62
Popper and air bubble curtain	41	75
Strobes and popper	*	70
Strobes	*	57
Strobes and air bubble curtain	82	−48
Strobes, air bubble curtain, and popper	*	69

Note: Effectiveness was calculated as (C− E)/C × 100%, where C and E are the numbers of fish netted in the control and experimental structures, respectively

*Tests were not performed in 1985.

two structures. Under control circumstances, both structures should theoretically have collected the same number of fish. Thus, a correction factor based on paired control tests was applied to other test results to prevent the data evaluation from being skewed by this phenomenon.

Nearly all the fish caught during Site 1 testing were adult alewife, a schooling pelagic species common to the Great Lakes. Table 1 indicates the effectiveness of each barrier or combination of barriers in diverting alewife. Because of problems with the experimental strobe lights, tests with these devices were limited in 1985.

The popper, operating alone, was the most consistently effective barrier tested, reducing entrainment at the experimental structure by 73–78%. On the basis of hydroacoustic monitoring of fish movements in the immediate area of the field test structures, the popper's range of influence was estimated to be 33 ft (10 m). With poppers mounted on the face of an intake structure, it may therefore be possible to maintain a zone approximately 33 ft in front of the intake that is relatively free of alewife.

Results for the air bubble curtain testing were inconclusive. Although ineffective during the 1985 test period, the air bubble curtain reduced entrainment by 62% in 1986. This inconsistency may be related to a higher current velocity in 1985, which could have affected the density and continuity of the curtain. Combining poppers with the air bubble curtain and/or strobe lights also reduced alewife entrainment significantly, but the numbers of tests for these combinations are insufficient to be statistically conclusive.

Site 2 testing

In contrast to studies at Pickering station, where a special test facility was available at the plant intake channel, tests at Central Hudson Gas & Electric's Roseton station (Site 2) used the entire shoreline intake structure. Poppers and strobe lights were positioned in front of each opening in the intake structure, and a double row of air bubble hoses was anchored to the floor of the Hudson River around the intake structure from the shoreline upstream to the shoreline downstream. Because the entire intake was used for both control and experimental tests, paired control and experimental tests were conducted in sequence. The plant's traveling screens were used instead of nets as the fish collection device.

Another major difference between sites 1 and 2 was the variety of fish. Whereas testing at Pickering station involved a single species (alewife), testing at Roseton station typically involved a variety of species—primarily white perch (37%); bay anchovy (36%); and a number of *Alosa* (21%), such as American shad, blueback herring, and alewife. Moreover, the prevalence of any particular type of fish at Roseton station varies considerably during the two major impingement periods, most commonly spring (March–April) and fall (August–November). Because the testing of barriers and barrier combinations was random by design, the seasonal changes in prevalence of fish species make the process of data evaluation more complex and in some cases make results less absolute.

In addition, Site 2 offered a unique opportunity for testing in two different source water environments (freshwater river and brackish water estuary) at a single location. The Roseton station's location on the lower Hudson River means that during the spring, the intake source water is predominantly fresh from snow melt runoff; during the summer and fall, however, the intake source water can become brackish from tidal seawater intrusion. Therefore, two years of testing (1986–1987) were discussed at Roseton station.

Site 2 testing was conducted on a 24-hour basis. Each day was subdivided into four 6-hour segments—day, dusk, night, and dawn. Within each segment a 3-hour experimental test and a 3-hour control test were conducted, with the sequence randomly selected.

Because fish impingement at Roseton station did not follow historical trends in 1986, the original spring/fall field test schedule had to be adjusted. Relatively low numbers of fish were entrained during the spring, so testing was delayed until mid-July and continued through the end of November, when the numbers of fish were sufficient to obtain statistically valid data. During that period, 375 paired tests were completed.

Table 2 summarizes the effectiveness of each barrier or combination of barriers in diverting fish from the Roseton station intake system. In comparison with the previous Site 1 field test results, the Site 2 results were somewhat surprising in several respects.

Table 2
EFFECTIVENESS OF BEHAVIORAL BARRIERS
(Site 2 1986 field test results—%)

Barrier	White Perch	Bay Anchovy	*Alosa**	American Shad	Blueback Herring	Alewife	Overall
Popper	–8	14	8		28		3
Air bubble curtain	–20	30	4				
Popper and air bubble curtain	–15	68	6		16		7
Strobes and popper	65	...	56		69		56
Strobes	43	–	9		11		23
Strobes and air bubble curtain	51		79	–	83		62
Strobes, air bubble curtain, and popper	–24	–	–17		–24		–19

Note: Effectiveness was calculated as $(C-E)/C \times 100\%$, where C and E are the numbers of fish collected during control and experimental testing, respectively

*The species *Alosa* includes American shad, blueback herring, and alewife.

- Strobe lights and strobe light combinations (which received only limited testing at Pickering station) consistently exhibited the greatest effectiveness in diverting fish. This finding was unexpected because high turbidity levels in the Hudson River limit effective strobe light transmission distances.
- Poppers were ineffective in diverting fish. Because of the success of poppers in diverting alewife at Site 1, their failure to divert *Alosa* (of which alewife is a member) at Site 2 was unanticipated.
- Although there appeared to be an additive effect (benefit) when combinations of two behavioral devices were used, no further increase in diversion effectiveness was observed when all three devices were operated simultaneously.

Future activities

The differences between the results obtained at the Pickering and Roseton stations may be due to a number of factors, and they highlight the importance of continued field testing under RP2214 for different source water environments. Testing at Roseton station will continue through the end of this year and will be followed by testing at an offshore intake in a marine environment during 1988.

EPRI's commitment to fish protection is not limited to thermal power plants. Under RP2694, funded in the Advanced Power Systems Division, EPRI is studying methods for protecting fish during downstream migration at hydroelectric plants; behavioral barriers may offer a suitable means of guiding fish to spillways or bypasses. In fact, because of the similar concerns at both types of plant, EPRI is sponsoring a joint conference on fish protection at steam and hydro power plants. The conference will be held October 28–30, 1987, in San Francisco. Papers presented will summarize progress on RP2214 and RP2694, as well as other recent advances in the design, operation, evaluation and testing, and biologic performance for a range of approaches to fish protection.

Industrial Applications

Heat Pumps for Industrial Processes

by Alan Karp, Energy Management and Utilization Division

Like their space-conditioning counterparts, industrial process heat pumps operate on the principle that the temperature of a vaporized working fluid increases when it is compressed. The working fluid can then be condensed, thereby releasing its latent heat content for use by the process. Under the right circumstances, the energy made available to the process in this manner will be many times that required to perform the compression, thus providing a net energy saving that can more than offset

ABSTRACT *The difficulty of determining appropriate candidate applications has significantly slowed the introduction of heat pump technology into the industrial sector. Industrial process systems are typically complex assemblages of many fluid streams that require various degrees of cooling and heating. The resulting large numbers of heat sources and heat sinks complicate system energy analyses and make estimates of heat pump costs and benefits difficult to ascertain. An EPRI-developed software package will soon be available to provide valuable insights into the potential for cost-effective heat pump implementation in such systems. This computerized analysis of potential heat pump effectiveness relies on mathematical techniques that combine all streams—those that require heating and those that require cooling—into composite curves, plotted in terms of temperature and enthalpy. The curves identify points of minimal temperature difference that are indicators of the trade-off between energy costs and capital investment. EPRI's PC-based software package will be able to screen industrial process stream systems for potential heat pump use, indicate thermodynamically appropriate heat pump locations and sizes in the system, and perform preliminary cost-benefit analyses.*

the capital and operating costs of the heat pump.

In closed-cycle heat pumps, the compressor operates on a working fluid—typically a refrigerant, such as Freon or ammonia—that receives low-temperature heat from the process through a heat exchanger and returns higher-temperature heat to the process in the same manner. In semiopen cycles, the working fluid is a process stream, and only one heat exchanger is involved, either to heat the process stream working fluid at the cold end or to deliver heat back to the process at the hot end. When a process fluid is compressed and returned to the process without any heat exchangers being used, the cycle is said to be completely open.

Although industrial process and space-conditioning heat pumps are thermodynamically comparable, they have little else in common. Not the least of their many differences is the fact that industrial process heat pumps have no predetermined function. For a residential application, the heat pump's function (providing a certain level of space or water heating), heat source (the outside environment), and heat sink (the living space) are known, at least in broad terms. A typical industrial process, however, involves dozens, even hundreds, of potential sources and sinks and presents no obvious guidance on how heat pumping might cost-effectively (much less optimally) satisfy process cooling and heating needs.

In the main, engineers have dealt with this situation in an ad hoc fashion. A common approach is to identify process streams that are being condensed or vaporized, thereby releasing or accepting, respectively, large latent heat loads at a more or less constant temperature. Where a condensing load is large enough and requires only a modest increase in temperature to satisfy a process heat requirement and where process considerations and plant layout permit, it may prove cost-effective to install a heat pump. However, even if this is a technically sound application (and it may or may not be), such an approach affords no insights into how the proposed heat pump's costs and benefits compare with those of alternative means of reducing energy consumption.

The prevalence of this ad hoc approach notwithstanding, some prior work had been done to establish general principles that provide guidance for effectively positioning heat pumps within an industrial process-stream network. That work was done in England as part of the development and application of a unique process design and analysis technique known as pinch technology.

In analyzing a process, all streams that require cooling can be mathematically combined into a single hot composite curve of temperature versus enthalpy; similarly, all streams to which heat must be added can be represented by a single cold composite curve (Figure 1). The shape of these curves will vary from process to process, but they will usually exhibit a point of least separation, that is, a point at which the temperature difference between them is at a minimum (ΔT_{min}). That point is called the process pinch.

As shown in Figure 1, the composite curves clearly indicate the potential for simultaneously satisfying process heating and cooling needs through process-to-process heat exchange. Also clearly established is the minimal heating and cooling that must be supplied from sources external to the process.

For that portion of the process that is above the pinch temperature, there is a net heat deficit; below the pinch temperature, the process has a net heat surplus. In the region where the hot and cold composite curves overlap (darker color region), process-to-process heat exchange has the potential of meeting the heating and cooling needs of the system. That is, heat can be extracted from the hot streams and delivered to the cold streams, effectively cooling the one and heating the other. To the left of that darker region, process-to-process heat exchange is unavailable because there are no cold streams, and external cooling (e.g., use of cooling water) is required; likewise, to the right of the region, external heating (e.g., steam heaters, furnaces) is required.

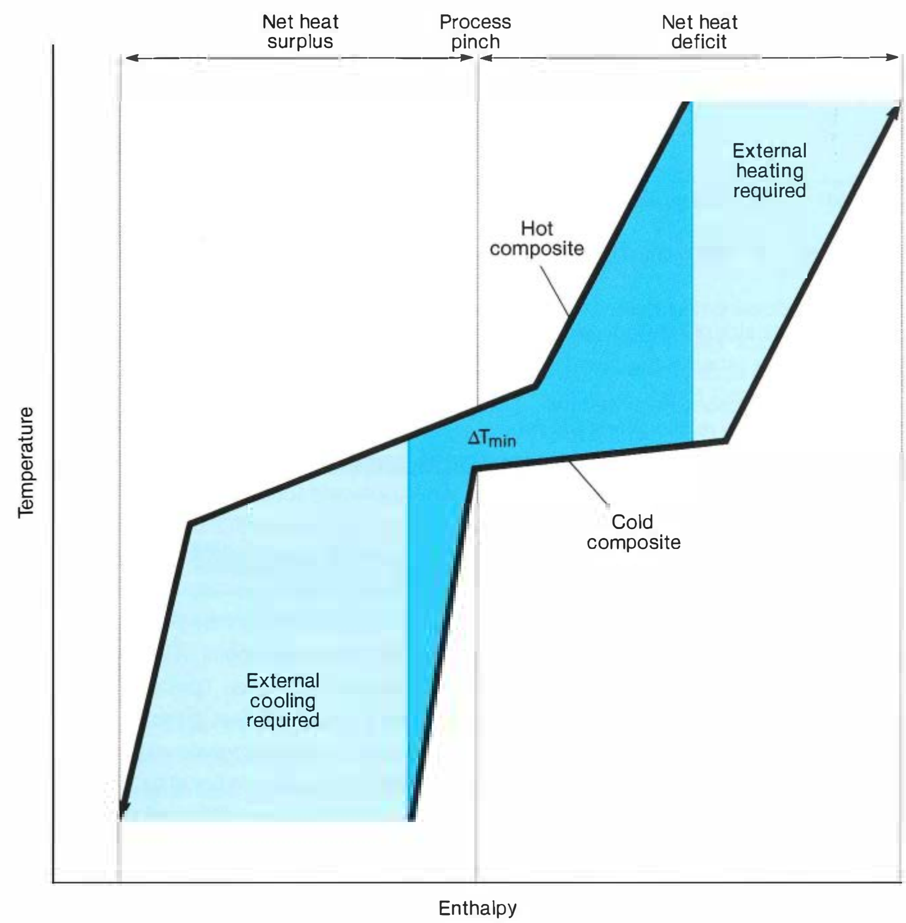


Figure 1 Hot and cold stream composite curves. The pinch is the point at which the temperature difference between the two curves is at a minimum (ΔT_{min}). In the region where the hot and cold composite curves overlap (darker color region), process-to-process heat exchange has the potential of meeting the heating and cooling needs. At points on the hot composite curve that lie to the left of the darker region, external cooling is required; at points on the cold composite curve that lie to the right of the region, external heating is required.

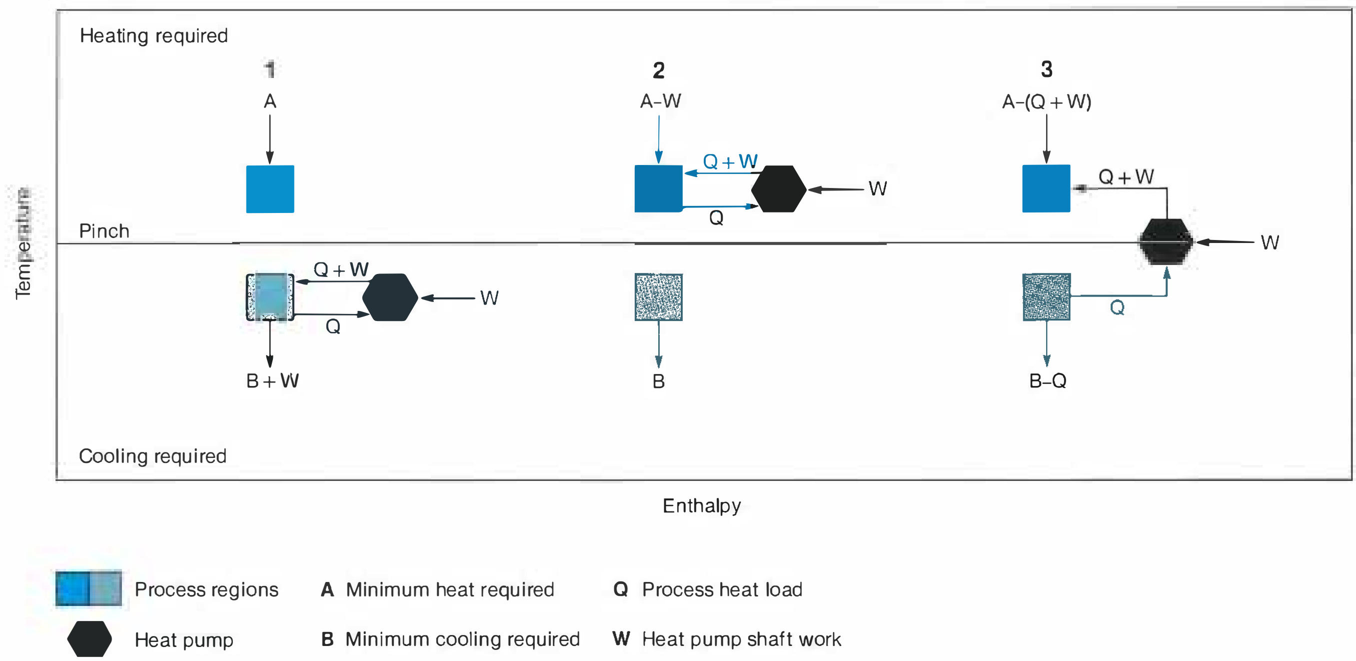
Given these observations, it is clear that any heat supplied to the process in excess of the minimum identified on the composite curves will not be useful but instead will cascade through the pinch and increase the requirement for external cooling. Similarly, it is clear that using externally supplied cooling above the pinch and externally supplied heating below the pinch are practices that are incompatible with the objective of minimizing energy consumption.

This analysis has profound implications for the placement of heat pumps in industrial process streams. Clearly, heat pumping can be beneficial to the overall process only if it takes heat from below the pinch, where heat is in surplus, and makes it available to the process above the pinch, where there is a heat deficit. If placed entirely below the pinch (Figure 2.1), the heat pump would actually aggravate the heat surplus below the pinch by an amount equal to the shaft work expended (W). Increased cooling would then be required to remove this heat increment from the system. Assuming the heat pump to be electrically driven, this amounts to placing a resistance heating element in the cooling system, hardly a prescription for energy efficiency. If the heat pump is placed entirely above the pinch (Figure 2.2), there is still no net energy saving. The heat requirement is reduced by W, but an equal amount of shaft work is required. Thus there is no net energy saving to compensate for the added heat pump equipment investment.

Moreover, for an electric heat pump, the cost of the energy trade-off (electricity versus fossil fuel) will almost never be attractive. Placing the heat pump across the pinch, however, decreases the heat deficit by $Q + W$ and reduces the cooling load by Q (Figure 2.3).

Proper positioning of the heat pump relative to the process pinch, therefore, is prerequisite to any saving in energy; however, of itself it neither defines the size of the heat pump nor guarantees either its cost-

Figure 2 Effects of heat pump placement. The regions above the pinch require heat; those below require cooling. In (1) a heat pump is added but is improperly located below the pinch, in which position it increases the heat load that must be removed by an amount ***W***. In (2) the heat pump is located above the pinch. The required heat input is diminished by ***W***, but ***W*** is the energy required to drive the heat pump—net energy required equals $(A - W) + W = A$; that is, there is no net energy saving to compensate for the cost of the heat pump. In (3) the heat pump is properly positioned across the pinch so that both the necessary heat input [heat required equals $A - (Q + W) + W = A - Q$] and the heat loads that must be removed are reduced by the amount ***Q***.



effectiveness or its economic merits when compared with those for incremental heat recovery through process-to-process heat exchange. To address these questions additional insights are needed.

The composite curves shown in Figure 1 can be shifted on the enthalpy axis so as to be separated by different values of ΔT_{min}. The effect of increasing ΔT_{min} by shifting the curves horizontally is to decrease the region of overlap between the hot and cold composite curves, thereby reducing the amount of process-to-process heat exchange that can be used. This in turn increases the need for externally supplied cooling and heating. On the other hand, larger values of ΔT_{min} also imply greater temperature driving forces for heat exchange, which reduce the heat exchanger surface area needed and, therefore, the associated capital costs. Smaller values of ΔT_{min} imply the reverse—less need for externally supplied heating and cooling but increased costs for process-to-process heat exchange. In short, ΔT_{min} is an indicator of the trade-off between operating costs (energy requirements) and capital investment (heat exchanger network). Once these relationships are recognized, some important characteristics of the process system can be analyzed before design work is undertaken. This analysis is facilitated by the use of a highly accurate algorithm that was developed for estimating heat exchanger surface area requirements and costs from the composite curves.

Different values of ΔT_{min} can be considered to optimize the system-specific trade-off between capital costs and energy requirements (Figure 3).

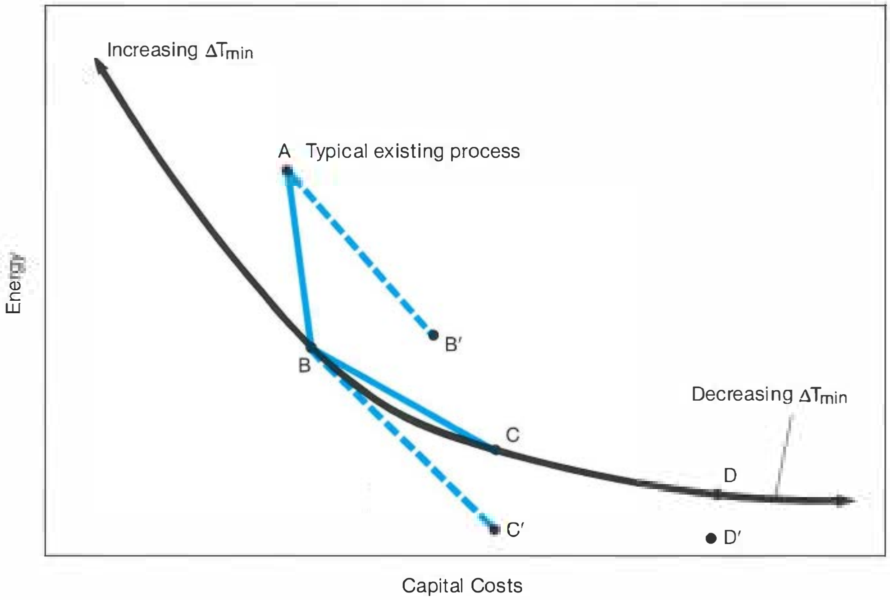
Because most existing industrial process streams are not as well designed as they could be, a typical existing process can be represented by point *A*, which is above the ΔT_{min} curve. One implication is that the process is using more energy than it would if its heat exchange network had been optimally configured. In many cases, existing networks can be restructured, reusing most of the existing heat exchangers and adding only a small amount of additional surface area, to reduce energy consumption, for example, to point *B*. Because the slope of the line from *A* to *B* represents the incremental energy saving (or operating cost reduction) divided by the incremental area (or capital investment), it is effectively proportional to simple return on investment.

As Figure 3 suggests, poorly heat-integrated processes (point *A*) can often be dramatically improved (point *B*) with low capital investment, fast payback projects. However, further improvements in energy efficiency through additional heat exchange (e.g., points *C* and *D*) tend to become progressively less attractive, as the additional heat exchanger area becomes incrementally less cost-effective at higher levels of thermal efficiency.

With heat pumping, however, this trend of diminishing relative cost-effectiveness is reversed. At high levels of process energy use (point *A*), it is difficult for the improvement in efficiency through heat pumping (e.g., point *B*) to be more attractive economically than the cost-benefit ratio achieved by revised heat integration. However, as thermal energy requirements decrease, heat pumping becomes more competitive—particularly as it provides a means of reducing energy consumption (points *C′* and *D′*) below the level that is economic for heat exchange alone (points *C* and *D*).

Still additional insights are provided by a continuation of the composite curve analysis. For example, logical opportunities for heat pumping can be made apparent, as can quantifiable limitations on the amount of heat pumping that can be beneficially employed. In this regard, it is interesting to note that a heat pump designed to match a large condensing load with a large process heat requirement would not be cost-effective, regardless of its capital costs and no matter how high a coefficient of performance it might have, if the two loads are on the same side of the process pinch. This is an example of an insight that would not be revealed in a conventional analysis.

Figure 3 Trade-off between capital cost and energy requirements for various values of ΔT_{min}. Points on the ΔT_{min} curve are optimized. Modifications (exclusive of heat pumps) to move from point *A* to point *B* can be achieved at modest cost (for increased heat exchanger surface area) and return substantial energy savings. Further reductions of energy consumption to points *C′* and *D′* are not economically feasible for heat exchanger increases alone; however, they may be achievable with heat pumping.



This and similar insights into appropriate heat pump placement and cost-effective use served as the foundation for EPRI's systematic procedure for screening industrial processes for heat pump applications and for performing preliminary cost-benefit analyses (RP2220). A PC-based software package to execute this procedure is now in an advanced stage of development and will be introduced at industrial process heat pump workshops to be held in Dallas, Philadelphia, and San Francisco later this year.

Nuclear Plant Corrosion

Primary Water Stress Corrosion Cracking Remedies

by Allan McIlree, Nuclear Power Division

In the past 16 years the nuclear industry has observed initiation of primary water stress corrosion cracking (PWSCC) from the reactor side of pressurized water reactor (PWR) steam generators tubed with mill-annealed Ni-Cr-Fe alloy 600 (Inconel). This cracking has occurred in highly strained (stressed) regions of rows 1 and 2 U-bends and in expansion regions within the tubesheet (Figure 1, p. 53). Cracking has been almost exclusively limited to recirculation-type steam generators. The steam generators in one of the first PWR plants to have this type of degradation had to be replaced after 14 years of operation. Within the last several years, PWSCC has also been observed at less-strained regions at tube support intersections, where secondary-side corrosion of the steel support plates has squeezed the tubes and dented them.

PWSCC may or may not be related to denting. Denting-related cracking can be minimized or eliminated by following recommendations in the EPRI Steam Generator Owners Group "PWR Secondary Water Chemistry Guidelines, Rev. 1" and therefore should not be a continuing problem. Nondenting-related PWSCC, on the other hand, has been a continuing problem in certain types of steam generators. Of the 47 plants operating at least 5 years (started up before 1980), over half have shown varying degrees of PWSCC. Over time, occurrences have ranged from the cracking of a few tubes to extensive cracking of thousands of expansion transitions. In several cases,

ABSTRACT *Many pressurized water reactor steam generators have exhibited intergranular stress corrosion cracking of alloy 600 tubes, initiating from the reactor side at U-bends, tubesheet expansion regions, and tube support intersections. Research by EPRI and others has sought to understand the cracking phenomenon and to develop ways to prevent its occurrence and/or curb its growth. A number of corrective measures are available for treating tubes; others are being developed. Treatment includes application of mechanical measures, such as plugs, sleeves, and peening, or adoption of operating procedures to control environmental parameters, such as reducing temperature and water hydrogen content.*

cracking occurred during the first year of operation.

Although many plants have had PWSCC problems, many other plants of similar vintage and fabricated by other manufacturers have so far been free of this degradation. This statistic is encouraging, but the oldest of these plants have been in operation about 15 years, and PWSCC may still become a problem at some of these plants before they reach the end of their design life.

Causes and consequences

As in all stress corrosion cracking, PWSCC requires the coincidence of three factors: susceptible material, aggressive environment, and tensile stress. Operating experience and laboratory tests have demonstrated that alloy 600 tubing in some heat treatment conditions will crack in a normal PWR primary water environment. The rate at which cracking occurs appears to depend primarily on the material microstructure, temperature, and local tensile stresses (residual and applied).

Material susceptibility appears to correlate most strongly with carbide morphology (i.e., the number of grain boundary carbides); however, there is also some correlation with grain size, material strength, and hardness. Tubes with copious grain boundary carbides (intergranular carbides) are less susceptible to PWSCC than are tubes with few grain boundary carbides and copious carbides within the grain (intragranular carbides). The main fabrication variable that controls carbide morphology is the tubing temperature during the final mill anneal heat treatment. Higher temperatures generally result in less-susceptible material.

The tensile stresses are the sum of residual plus operating stresses. Residual tensile stresses are induced in the tubing during fabrication, and in recirculating-type steam generators these stresses are not reduced by any stress-relief heat treatments. On the basis of operating experience and laboratory tests, researchers believe that tensile residual stresses on the inside of the tube are much higher than the operating stresses and can equal or exceed the material yield strength. Many of the remedial measures developed are directed toward reducing the tensile residual stresses or applying a compressive residual stress on the surface by peening.

Consequences of PWSCC may include secondary-side contamination, possible derating of the plant electrical output if the number of plugged tubes goes beyond the available tube margin, unscheduled outages caused by excessive leakage limits, or increased risk of sudden tube rupture.

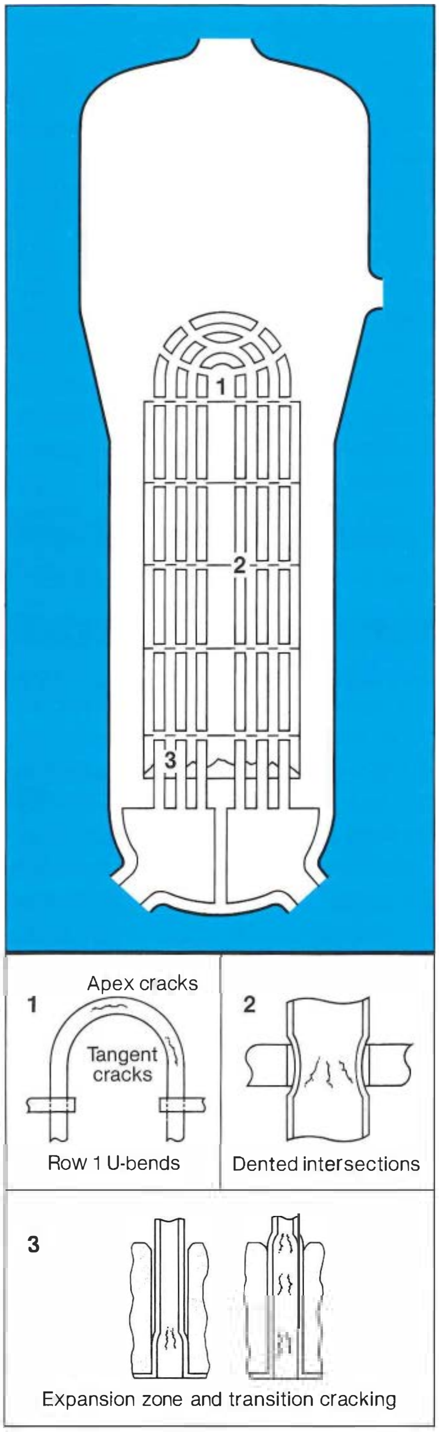
To date, general experience with U-bend cracks has been that the leakage is relatively low and increases gradually over a long period (i.e., months). The major exception to this sequence has been U-bend apex cracking that resulted from high ovality. (High ovality results from initial fabrication or from flow slot closure caused by denting.) In these cases, a few tubes have ruptured suddenly, causing large leaks. Plant owners have remedied these problems by plugging the leaking tubes or by plugging all row 1 tubes to prevent leakage.

In expansion transitions and expanded areas within the tubesheet, leakage is relatively slow and increases gradually over long periods. No cases of sudden rupture of tubes in the expansion region have been reported. Where the cause of PWSCC has been identified (e.g., rolling abnormalities) and the cracking affects small numbers of tubes, the general course of action has been to inspect and then plug the affected tubes to prevent additional problems. This solution is not practical, of course, where large numbers of cracked tubes are present or anticipated. In such cases, the approach to date (particularly in Europe) has been to accept small amounts of leakage while corrective measures were being developed. This approach, however, could eventually require steam generator replacement.

Corrective measures

The only currently viable corrective measures for tubes in which cracking has already occurred are to install plugs or sleeves. The choice between the two generally depends on the number of excess

Figure 1 Locations of alloy 600 tube cracking in recirculating-type PWR steam generators. Cracks have been reported in the U-bend region of first- and second-row tubes, at roll transitions, at roll expanded areas within the tube sheet, and at dented tube support intersections.



tubes (plugging margin) and how extensive the cracking problem is or is likely to become. Commonly used techniques for tube plugging include welding of solid plugs, use of explosive plugs, and use of mechanical plugs.

Provisions for plug removal (e.g., tapped holes in the plug) are common. Solid plugs are inserted and welded to the tube. The welding procedure varies; the variations include the addition of weld filler materials and the use of filler material integral to the plug. In the latter technique, only external heating is required to form the weld. Systems are available for manual, semiautomatic, and automatic welding of solid plugs.

One explosive plugging technique consists of inserting a plug with a built-in charge, which is detonated when the plug is in place. The plug material expands and becomes tightly bonded to the tube material. No welding is used in this process. Another explosive plugging technique uses a hollow plug with a sealed inner end. The plug is inserted into the tube; the charge is inserted into the plug and detonated. The plug end is then welded to the tube. During this operation, the tube-tubesheet weld may also be repaired, if necessary.

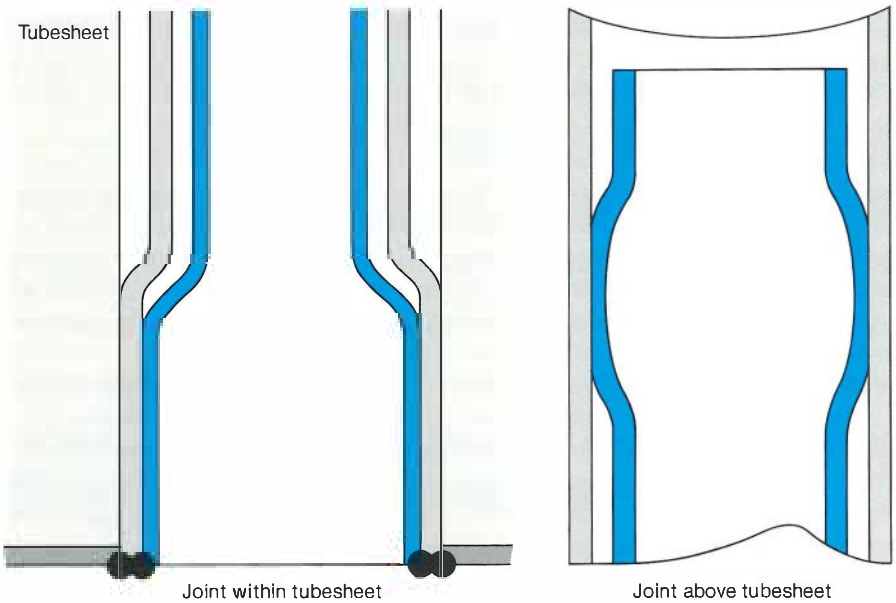
However, some explosive techniques may create other problems. At least three utilities have steam generators, the plugs of which leaked following the use of an explosive technique to plug leaking tubes. Because the tubes in question were plugged over a wide period (1973–1977), experts speculate that the cracking and leaking are not related to a single batch of plugs but to a faulty technique. One hypothesis is that the process produces very large plastic strains in the tube plug wall (over 100%) and leaves high residual stresses at tube plug corners. This phenomenon, in turn, leads to highly stressed circumferential seams around the plug. The seams then crack within a short period (sometimes less than 60 days), and leaking recurs in those tubes already plugged for leakage (as opposed to those plugged for leak prevention). Experience has shown that failed plugs do not open up and leak increasingly but that they leak at a steady rate over a long period. In reverse-leak testing, during which the secondary side is pressurized and the primary side is vented, the reverse pressure closes cracks in tube plugs and seals them. Therefore, it has been easier to identify cracked tube plugs by using only a static head of water on the secondary side.

Most nuclear steam supply system (NSSS) vendors now offer installation of mechanical plugs. The mechanical plugs are installed without welding or explosives and may be removed later. Through 1986, experience with mechanical plugs has been good.

Tube sleeving is an alternative to plugging. Normally, when degradation of a steam generator tube wall exceeds a specified limit, maintenance personnel take the tube out of service by installing plugs at the inlet and outlet. However, each tube removed from service represents a loss of heat transfer surface and a slight reduction in area for primary coolant flow. To prevent this loss, techniques have been developed for installing sleeves inside tubes. As Figure 2 shows, the sleeve is a smaller-diameter tube that slips into the original damaged tube. Depending on the specific sleeve design, the ends of the sleeve are expanded, brazed, or welded to provide both a seal and a redundant load-carrying path. To date, sleeves have been used to repair damage caused by secondary-side intergranular corrosion (IGC) in the tubesheet crevice, secondary-side pitting, and IGC in the sludge pile region. More than 15,000 sleeves have been installed in at least seven plants. Details of sleeve designs and installation methods are generally proprietary, and the amount of information available limits the descriptions given here.

Other ameliorative measures are being developed. One such technique is to dissipate residual stresses induced in the tubing during fabrication. EPRI has sponsored work to demonstrate in situ thermal stress relief that reduces residual stresses in row 1 U-bends by means of a wire-wound electrical resistance heater (NP-4364-LD). In stress corrosion tests, U-bends stress-relieved for

Figure 2 Sleeve application. Typically, the sleeve is thermally treated (TT) alloy 600 or 690, alloy 600 (TT) clad with either nickel or alloy 625 on the outer diameter. The lower end of the sleeve (left) is generally expanded and welded to the original tube to provide a seal. The upper sleeve (right) may be treated similarly, or it may be brazed.



5 and 15 min at 1300°F (704°C) and 15 min at 1450°F (788°C) showed a marked difference when tested under prototypic environmental conditions. Their crack-free life was improved by more than a factor of 10, compared with non-stress-relieved controls. NSSS vendors continued developing this heater technique and carried out the first commercial rows 1 and 2 U-bend stress relief service in May 1986. Since then, similar treatments have been applied at more than a dozen plants.

Peening of PWR steam generators was developed principally by Electricité de France and Trabel (Belgium). This technique forms a thin compressive stress layer on the inner diameter (ID) surface of expansion regions (NP-5249, Vols. 1 and 2). The compressive stresses serve to inhibit the initiation of PWSCC, which occurs only in the presence of high tensile stresses. Shot peening is the blasting of ID surfaces with small metal, ceramic, or glass shot. Rotopeening uses shot bonded to fabric in a flapper wheel. The impact of the shot on the tube ID surface creates a thin work-hardened compressive layer.

Both shot and rotopeening methods were being developed, but rotopeening was the technique selected for the first plant application (January 1984) because of concerns about the spread of contamination and abrasive particles associated with shot peening. Rotopeening was applied to two plants in early 1984 before they began commercial operation. Because rotopeening requires the use of remote tooling in a radioactive plant, the developers readdressed the concerns about the spread of contamination in shot peening. The first operational plant was shot-peened in July 1985.

Only rotopeening was available in the United States until late in 1985, when shot-peening services became available. During 1985 and 1986, 9 of the 13 domestic plants identified as susceptible to PWSCC were peened. The remaining 4 plants are scheduled for peening during 1987. Although the Steam Generator Owners Group played only a minor part in the development of the peening technology, its role as a cooperative group of domestic and foreign utilities provided a focus for technology review and an arena for rapid technology transfer.

Full steam generator bundle stress relief is a treatment used for the manufacturing of once-through steam generators. To date, these generators have not experienced PWSCC even though their tubing has been mechanically expanded. In principle the treatment is designed to stress-relieve the pressure vessel steel in the temperature range of 1022–1130°F (550–610°C). During this treatment, peak residual stresses in the tubing are also reduced, and metallurgical changes (grain boundary carbide precipitation) can occur to improve SCC resistance. This favorable operating experience, as well as the experience gained from steam generator replacements, prompted the Belgians to consider global heat treatment. The steam generator replacement experience in heating attachment welds indicated that with proper insulation and control of heaters, the entire tubesheet could be heated. Although the method was never implemented, Belgian researchers did enough preliminary analysis and testing to demonstrate its feasibility (NP-5249, Vol. 3).

Environmental approaches

Reduced primary coolant temperature service experience and laboratory tests have shown that PWSCC is strongly influenced by temperature. Laboratory test data indicate that the rate of attack varies like a standard thermally activated process, that is, in accordance with Q/RT, where Q is the activation energy of about 40 kcal/mole, R is the gas constant (1.985×10^{-3} kcal/K mole), and T is the absolute temperature in degrees Kelvin. Using this relationship, operators can increase lifespan by decreasing a typical hot leg temperature (Table 1). As the data show, a large improvement would require a significant decrease in temperature, which is not practical as a long-term solution. However, it may be worth considering in some cases as a short-term way of reducing the rate of damage while other remedial measures are prepared. It should be noted that a similar temperature reduction (40°F; 22°C) was successfully used at one plant to reduce the rate of secondary-side IGC. However, the 40°F reduction did result in

Table 1
IMPROVED LIFESPAN BY TEMPERATURE REDUCTION

Temperature °F (°C)	Factor of Improvement
610 (321.1)	1.0
600 (315.6)	1.4
590 (310.0)	1.9
580 (304.4)	2.7
570 (298.9)	3.7
560 (293.3)	5.3

about a 25% loss of power output.

Although large reductions in reactor coolant temperature are economically prohibitive for long periods, it may be worthwhile to reduce hot leg temperatures as much as possible, while still maintaining 100% power output. For example, even a 10°F (5.6°C) reduction can be expected to reduce the rate of attack by about 40%.

Another possible approach for reducing the aggressiveness of the environment is to reduce the hydrogen concentration in the primary water to the lower end of the allowable range. Tests have shown that hydrogen accelerates the rate of cracking when added to pure water, and Electricité de France tests have shown that large concentrations of hydrogen (700 cm^3/kg) have a similar effect in primary water. However, the effect of small changes in hydrogen concentration in primary water has not been quantified, and it thus remains problematic. Changing water from no hydrogen to about 20–25 cm^3/kg decreased the time to SCC initiation by about a factor of 5 for material with moderate amounts of cold work. Researchers suspect that increasing the hydrogen content, as would be allowed by normal primary water specifications, would result in an acceleration of primary-side attack, and they are studying this phenomenon. The Steam Generator Owners Group has recommended operation at the low end of the 25–50 cm^3/kg specification.

The challenge of PWSCC of steam generator tubing has been met by utilities individually and cooperatively by defining the condition promoting the degradation and developing corrective and ameliorative measures. Plugging and sleeving corrective measures remain viable options for cracked tubing, whereas peening and stress-relief ameliorative measures offer prevention of further crack initiation. It remains to be seen how effective these procedures will eventually become, and the newly formed EPRI steam generator reliability project will take the lead in assessing their effectiveness.

Fuel Planning

Natural Gas Reserves: Exploration and Development Costs

by Jeremy Platt, Planning and Evaluation Division

ABSTRACT *The price of natural gas and its availability are important in evaluating new power supply options, fuel procurement, competition between gas and electricity end use, and levels of gas-fired self-generation and cogeneration. Attention to the underlying factors shaping the gas supply outlook was diverted recently by dramatic shifts in the gas market, by regulatory change, and by a much shorter-term focus on advantageous purchases. Still, the longer-term gas supply outlook remains controversial, and real progress has been needed to reduce the gas resource and cost uncertainties in utility and R&D planning.*

Beginning in 1981 EPRI and the Gas Research Institute cosponsored a research project by the Colorado School of Mines to determine and compare across geologic regions the costs of finding and developing undiscovered natural gas fields that are thought to exist in the United States. The results have now been published, and they provide a practical interpretation of the diverse geologic and economic conditions that apply to the nation's gas resources (P-5284). Unique in detail and scope, the effort opens new approaches for assessing the gas supply outlook. Some caution is required in interpreting the results, however, because of possible confusion over the distinction between gas resources and gas supplies.

What has been achieved is a disaggregated data base on resource characteristics and development costs for some 21,500 undiscovered natural gas fields presumed to exist in 36 geologic provinces across the United States (Figure 1). The total resources in these fields are estimated at 608×10^{12} ft^3, or more than 80% of the total estimated natural gas resources. The data base includes the following information.

- Field sizes (from <0.004 to 4×10^{12} ft^3 and higher)
- Depth of fields (5000-ft increments to 30,000 ft)
- Number of fields (by size and depth)
- Success ratios for exploration and development drilling
- Drilling costs by area, depth, and type of well
- Well recoveries by depth and size of field
- Marginal costs of developing estimated resources by category (probable, possible, and speculative), depth, and field size
- Cumulative distributions of marginal and average costs of developing estimated resources in each region

The distinction to be made is that these resource-related cost calculations are neither supply nor price projections. Even if the estimated resources do exist in the configurations proposed here and if the technology and effort of discovery and development follow expected patterns, there is no guarantee that the level of drilling called for will actually be reached or that the resulting supplies will be sold at prices sufficient to cover costs, sold at much higher prices, or sold at much lower prices. Thus, many additional assumptions about the gas market are necessary to project the dynamics of supply over time. Although this introduces more uncertainties, the premise of the effort is that over time, fundamental cost considerations increase in importance.

In themselves, the cost calculations are

1 Oregon
2 Sacramento
3 San Joaquin
4 California Coast
5 Sweetgrass Arch
6 Central Montana
7 Southwest Montana Thrust Belt
8 Wind River
9 Wyoming-Utah-Idaho Thrust Belt
10 Southwest Wyoming
11 Piceance
12 Paradox
13 San Juan
14 South Basin and Range
15 New Mexico
16 Permian
17 Williston
18 Anadarko
19 Bend-Ft. Worth
20 East Texas
21 Texas Gulf Coast, Onshore
22 Texas Gulf Coast, Offshore
23 Arkoma
24 North Louisiana-South Arkansas
25 Louisiana, Onshore
26 Louisiana, Offshore
27 Illinois
28 Black Warrior
29 Mississippi-Alabama
30 Michigan
31 Appalachia
32 Atlantic Coast-East Triassic

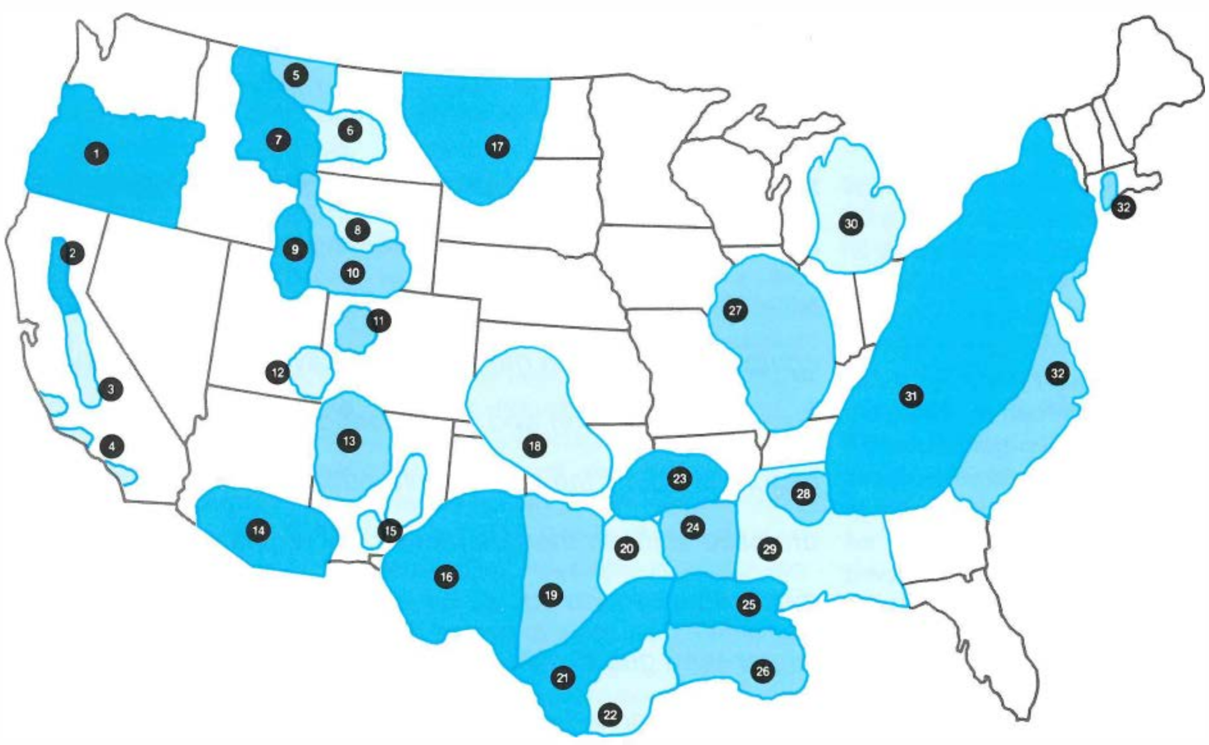


Figure 1 The geologic provinces that are estimated to contain 608×10^{12} ft^3 of natural gas reserves in some 21,500 postulated fields. The fields remain to be discovered and developed. About 564×10^{12} ft^3 of nonassociated gas is thought to exist in these fields, and 436×10^{12} ft^3 of that amount is contained in just 9 of the provinces.

Table 1
NONASSOCIATED GAS RESOURCES—COST DISTRIBUTION
(9 largest provinces*)

Province	Quantity (10^{12} ft^3)	Cost/10^3 ft^3 <$1	<$2	<$3
Wyoming-Utah-Idaho Thrust Belt	92.5	24.2	60.8	84.2
Anadarko, Deep	81.5	48.6	77.9	78.9
Appalachia	64.0	9.7	27.3	31.3
Southwest Wyoming	51.5	0.4	13.2	16.1
Permian	37.0	0	2.6	10.0
Louisiana, Offshore Shelf	34.4	3.0	12.2	19.9
Texas Gulf Coast, Onshore	27.7	2.4	5.5	13.3
Wind River	25.3	2.6	12.4	14.6
Texas Gulf Coast, Offshore Shelf	22.0	0	0	1.9

*Ranked by volume of estimated total gas resources.

useful for comparing one region with another or for comparing the costs of these potential resources with the costs of unconventional and supplemental sources of supply. Analysts can also use the data in targeting future efforts to improve the economic and geologic assumptions.

The 1982 resource estimates of the Potential Gas Committee (PGC) formed the starting point of this project. PGC is a technical group with broad geologic and geographic experience that has prepared and published biennial estimates of the potential supply of natural gas since 1964. The present work was performed independently by the Colorado School of Mines but with assistance from members of the PGC. Project investigators developed resource distributions by area and depth that were consistent with the PGC estimates. They also obtained regional data on exploration, production, and other costs from PGC, as well as from American Petroleum Institute, DOE, Bureau of Census, American Gas Association, and industry experts. A parallel study of drilling costs was conducted to derive appropriate regional cost-depth relationships. All these data and costs were translated to marginal costs of development in each region, using an economic model developed for this study by Operational Economics, Inc.

During the course of the project a number of sensitivity analyses tested the reasonableness and robustness of many of the assumptions, such as the sensitivity of the cost calculations to field size distributions (which range from the very large to the very small), to variations in success rates, to drilling costs, to field development patterns, and to discount rates. Further evaluations of the assumptions are recommended, but nonetheless a reasonable basis for consistent analysis was established by this project.

Field sizes, well recoveries, and well depths significantly influence the distribution of costs. Study statistics show an estimated 156×10^{12} ft^3 available at a cost of less than $\$1/10^3$ ft^3 and 393×10^{12} ft^3 at less than $\$3/10^3$ ft^3. All costs are in 1980 dollars at the wellhead and correspond, approximately, to $\$2.30/10^3$ ft^3 and $\$4.90/10^3$ ft^3, respectively, in 1986 dollars for gas delivered to the utilities. The importance of examining the economic dimension of the estimated gas resources becomes clear immediately. Twenty-five percent of the resource falls in the lowest-cost category, whereas 35% exceeds the higher-cost category. This cost distribution, itself offering a valuable perspective, is made more useful by the underlying regional details. These give us reason to be especially cautious of the calculations for the lowest cost category.

Some relevant considerations apply here. First, 36×10^{12} ft^3 of the 156×10^{12} ft^3 in the lowest-cost category is gas associated with oil, and its production will therefore be governed by oil economics. Second, 49×10^{12} ft^3 in the lowest cost category is estimated to occur in the Anadarko Basin at depths below 15,000 ft. Although the low costs may be realistic, the standstill of industry activity over the past four years or so suggests that much higher prices will be required. And third, PGC reduced its resource estimate for the Wyoming-Utah-Idaho Thrust Belt between 1982 and 1984. The effect was to reduce the estimate for this province from 24×10^{12} ft^3 to 8×10^{12} ft^3 in the lowest-cost category.

Taking all these points into account, 60×10^{12} ft^3 may be a more realistic estimate of the resources in the lowest-cost category, instead of 156×10^{12} ft^3, when they are considered in terms of gas supply dynamics. The conclusion to be drawn from this, however, is not that the lowest cost category is grossly overestimated in the study but

Table 2
NONASSOCIATED GAS RESOURCES
(10 largest lowest-cost provinces*)

Province	Quantity (10^{12} ft^3)
Anadarko, Deep	48.6
Wyoming-Utah-Idaho Thrust Belt	24.2
Appalachia	9.7
North Louisiana–South Arkansas	8.4
East Texas	5.5
Arkoma (Arkansas)	5.2
Louisiana, Offshore Slope	3.9
Louisiana, Offshore Shelf	3.0
Wind River	2.6
Texas Gulf Coast, Onshore	2.4

*Ranked by volume of gas at $\$1/10^3$ ft^3.

rather that the data base developed in the project is sufficiently detailed to permit users to bring their own judgment to bear on the supply implications.

The nonassociated gas resources, meaning gas reservoirs in which gas alone would be the principal target of exploration and the principal hydrocarbon recovered, comprise about 564×10^{12} ft^3, or 93%, of the resources examined in this project. The top nine geologic provinces in terms of total nonassociated gas resources are estimated to contain 436×10^{12} ft^3. The cost breakdown of the resources in these nine geologic provinces is quite varied, illustrating the importance of evaluating the areas from an economic and not merely from a geologic perspective (Table 1).

Table 2 ranks the top 10 provinces according to the volumes of estimated resources that fall into the lowest wellhead cost category. Anadarko is prominent, and the recently downgraded Wyoming-Utah-Idaho Thrust Belt is significant.

Acidic Deposition

Materials Damage From Air Pollutants

by Abraham Silvers and Charles Hakkarinen, Environment Division

ABSTRACT *Even the casual observer is familiar with the effects of deteriorating materials, including rusting bridges, peeling paint, and soiled stonework. Although much of this gradual deterioration occurs naturally, the combined action of weathering and corrosive man-made agents in the environment can accelerate the rate of damage. A portion of the increased rate of damage may be caused by the effects of air pollution, among them acid deposition. In addition to air pollution, other natural and man-made factors that can contribute to materials damage include moisture, sunlight, temperature fluctuations, wind, actions of microorganisms, and construction and maintenance practices. Damage is determined not only by the exposure of the material to corrosive agents but also by the type of material used. Field exposure studies and economic assessments are expected to suggest preventative action.*

Cost estimates of the annual damage from environmental pollution range up to the billions of dollars, although economic assessments of materials damage entail considerable uncertainty. Because of the potentially high economic cost and the possible relation to air pollution emissions (principally sulfur and nitrogen oxides) from electricity generation, EPRI has initiated research on the issue. The Environmental Data Analysis Program staff recently prepared a synthesis report on acid deposition and materials degradation (EA-5424). This report, designed for senior environmental managers in the electric utility industry, summarizes what is known and not known about the effects of acid deposition on materials and describes research programs under way in North America to resolve uncertainties. It addresses sensitivities of materials, atmospheric processes, and degradation mechanisms.

A large variety of man-made materials are exposed to the outdoor environment, and the concept of sensitivity is useful in establishing priorities for research. For a material to be considered sensitive, not only must it be reactive to deposited acidity but any resultant damage must be significant to society, a consideration governed largely by the application or use of the material. Thus, accelerated rusting of railroad track is not considered sensitive, as there is no loss of function. The premature failure of house paint or the corrosion of stone monuments, however, is considered sensitive. Sensitivity can be expressed simply as $S = (E \times L) \div C$, where E is the unit cost of replacement or maintenance, L is the amount of material lost per area exposed per unit of pollutant deposited, and C is the critical material loss (the amount of mass that can be lost before maintenance or replacement is required). By this definition, materials can be classified as sensitive if they are expensive to maintain or replace, have a high loss rate, or have a small allowable loss.

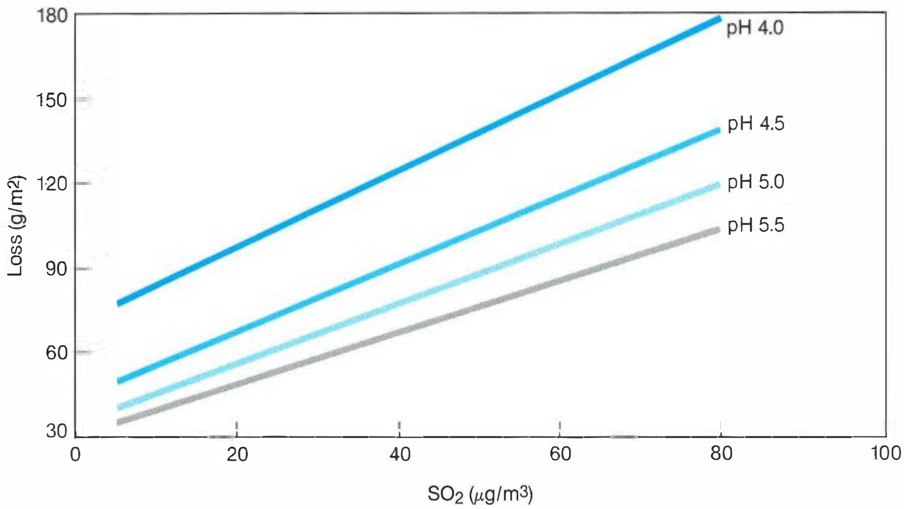
Materials with higher sensitivity to environmental degradation are generally used less frequently, possibly because society has made a long-term adjustment to avoid the use of materials less resistant to attack.

Corrosive air pollutants are deposited on surfaces in precipitation (wet deposition) or as gases or particulates (dry deposition). Some surfaces (e.g., weathering steel) may develop a protective coating during exposure, thus making them immune to further attack. Periods of wet and dry weather can also influence degradation—heavy rain showers may wash acidic particles off surfaces; evaporation of puddles may concentrate the remaining chemicals. Temperature fluctuations may produce thermal stress on materials and change airflow patterns that control deposition rates. Other atmospheric processes (e.g., sunlight, humidity) can degrade some materials directly or increase the surface adsorption of acidic gases.

Understanding the mechanisms of degradation is essential for deriving credible damage functions, making cause-and-effect attributions, and designing mitigative or control measures. Unfortunately, the mechanisms of degradation for most materials are poorly understood, and therefore few credible damage functions have been developed to date. EPRI's Environmental Risk Assessment Program cosponsored a project with the National Acidic Precipitation Assessment Program (NAPAP) to assess the extent and quality of available information that could be used to derive damage functions. Of the data available, the most reliable are for metals, particularly galvanized (zinc-coated) steel. On the basis of controlled laboratory and field experiments, the loss rate for zinc has been defined as a function of SO_2 exposure and precipitation acidity (Figure 1).

Data for deriving damage functions for other materials (e.g., stone, brick, wood, and painted surfaces) are very limited. It is known that properly fired brick is highly resistant to attack by air pollutants, whereas poorly fired brick is susceptible. Mechanism studies on paint, especially painted wood, in the past have emphasized erosion of the paint surface. Recent studies at the consumer level, however, suggest that so-called catastrophic failure (peeling and/or cracking) is a more common reason for repainting. Often catastrophic failure is related to improper preparation of surfaces for painting. Whether any damage has occurred often depends on the frequency of repainting. Since consumers may decide to repaint structures for reasons other than damage to the painted surface, the cost of paint damage is difficult to estimate.

Figure 1 Controlled laboratory exposures relate SO_2 concentrations and moisture acidity. The graph documents zinc corrosion loss over 10 years. The primary national ambient air quality standard for SO_2 is 80 $\mu g/m^3$.



Because damage functions must be developed in order to relate pollution levels to degradation, EPRI sponsored a study to determine the type of laboratory and field investigations that would best elucidate damage functions (RP2071-4). The study team recommended investigating the following three effects of acid deposition.

- Loss of bonding between paint and substrate
- Loss of material from stone, mortar, and concrete
- Effects on actual structures rather than on test plates

If the recommendations of the EPRI study are followed, it will very likely cost millions of dollars and take several years of investigation to discover the relevant mechanisms of damage. The U.S. Environmental Protection Agency is conducting some studies along these lines. Concurrently, EPRI's Environmental Risk Assessment Program has initiated a study of the cost of damage to paint that is attributable to acid deposition.

The goal of the study is to estimate the degree to which increased visible damage to paint prompts consumers (maintainers of buildings) to paint more frequently or otherwise incur higher painting costs. Once the desired information, target population, and most-effective means of polling the target population have been determined, a survey will be conducted and the results will be analyzed.

EPRI is working with NAPAP and the California Air Resources Board (CARB) to ensure that the study will complement research being conducted by these organizations—in particular, NAPAP's field exposure studies and CARB's planned economic assessment for the South Coast Air Basin. Our common goal is to improve the reliability of these economic estimates on the basis of the current understanding of the relevant physical and economic processes.

New Contracts

Project	Funding/ Duration	Contractor/EPRI Project Manager
Advanced Power Systems		
Support for High-Concentration Photovoltaic Performance (RP1415-15)	$52,750 8 months	Georgia Power Co./ *F. Dostalek*
Design and Implementation, IGCC Plant Training Simulator (RP2524-8)	$573,603 4 months	Simulation Assoc., Inc./ *G. Quentin*
Selective Agglomeration of Coal (RP2655-12)	$1,000,000 36 months	Alberta Research Council/*L. Atherton*
Phased Repowering, Gallagher Station (RP2773-9)	$186,000 9 months	Fluor Technology, Inc./ *D. Morris*
Geotechnical Drilling, Concrete Gravity Dam (RP2917-5)	$37,100 6 months	Stone & Webster/ *D. Morris*
Coal Combustion Systems		
Ash in Concrete Model Development (RP2422-16)	$60,000 6 months	Dunstan, Inc./*D. Golden*
Steam Turbine Rotor Line Assessment and Extension Evaluation of Retired Rotors (RP2481-5)	$1,189,400 37 months	Southwest Research Institute/*R. Viswanathan*
Control Systems Survey and Guidelines for Fossil Fuel Plants (RP2710-2)	$200,000 15 months	Babcock & Wilcox Co./ *S. Divakaruni*
Demonstration of EPRI Heat Rate Improvement Guidelines (RP2818-3)	$450,000 25 months	Virginia Power/*R. Leyse*
Electrical Systems		
Generic Guidelines: Life Extension, Plant Electrical Equipment and Systems (RP2820-2)	$169,600 7 months	Forensic Technologies International Corp./*J. Stein*
Effect of Crystallinity in Ethylene-Propylene Polymers (RP2899-1)	$80,900 13 months	Southwest Research Institute/*H. Ng*
Electrical and Mechanical Testing: Flexible Gas-Pressurized Cable System (RP7903-1)	$273,500 27 months	Power Technologies, Inc./ *T. Rodenbaugh*
Energy Management and Utilization		
Strategic End-Use Marketing (RP2381-17)	$64,700 7 months	Strategic Decisions Group/*C. Gellings*
Relationships Among Micromechanical Properties (RP2426-13)	$166,890 2 years	Daedalus Assoc., Inc./ *C. Sullivan*
Environment		
Plant Response to Interacting Stresses (RP2799-3)	$871,480 18 months	University of California at Riverside/*R. Goldstein*

Project	Funding/ Duration	Contractor/EPRI Project Manager
Nuclear Power		
Studsvik Super-Ramp II (RP1580-18)	$113,230 36 months	Studsvik Energiteknik Ab/ *J. Santucci*
Oconee Fuel Performance Examination (RP2229-4)	$203,000 11 months	Duke Power Co./*R. Yang*
Improved Centrifugal Pump for Nuclear Safety (RP2290-8)	$96,000 18 months	Innovative Technologies Laboratories/*J. Kim*
Diesel Start/Delay Program (RP2420-52)	$134,400 9 months	Westinghouse Electric Corp./*V. Chexal*
Orientation and Magnitude of Tectonic Stress From Borehole Measurements (RP2556-45)	$200,000 13 months	Empire State Electric Energy Research Corp./ *J. Stepp*
Protection Potential Against IASCC (RP2680-6)	$80,860 6 months	General Electric Co./ *L. Nelson*
International Piping Integrity Research (RP2756-1)	$600,000 38 months	Battelle Memorial Institute/*D. Norris*
Assessment of Borated Material Performance in Spent-Fuel Storage Racks (RP2813-4)	$49,400 7 months	Northwest Technology Corp./*R. Lambert*
Technical Repair Standard Development for Limitorque Valve Operators (RP2814-2)	$105,200 7 months	Advanced Technology Engineering Systems, Inc./*J. F. Lang*
Control and Diagnostics With NASA Technology (RP2902-1)	$182,780 1 year	Technology Applications/ *J. Naser*
Guidelines: Estimating Realistic Seismic Demand on Nuclear Plant Equipment (RP2925-4)	$193,800 8 months	URS Corp./*A. Singh*
Equipment Seal Life and Replacement (RP2927-1)	$49,500 6 months	Wyle Laboratories/ *G. Sliter*
Programmatic Support and Fact Finding Regarding Field Experience With SCC Remedies (RPS406-3)	$38,300 4 months	Dominion Engineering, Inc./*A. McIlree*
IGA/IGSCC Data Correction and Proceedings Preparation (RPS407-7)	$106,900 17 months	Dominion Engineering, Inc./*P. Paine*
Modification and Design Control (Q101-6)	$194,000 6 months	Cygna Energy Services/ *W. Bilanin*
Resin Leakage Detection (S401-3)	$99,990 1 year	Science Applications International Corp./ *T. Passell*
NDE Consulting Services (S404-6)	$39,000 7 months	Westinghouse Electric Corp./*C. Welty*
Support of BWROG–III NDE (T301-23)	$150,700 9 months	J. A. Jones Applied Research Co./ *M. Behravesh*

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

Proceedings: 11th Annual EPRI Contractors' Conference on Clean Liquid and Solid Fuels
AP-5043-SR Proceedings; $77.50
EPRI Project Manager: H. Lebowitz

Test and Evaluation of a 500-kW Vertical-Axis Wind Turbine
AP-5044 Final Report (RP1590-3); $32.50
Contractor: Southern California Edison Co.
EPRI Project Manager: F. Goodman, Jr.

Status of Commercial Wind Power: 1986 Survey
AP-5084 Final Report (RP1590-9); $47.50
Contractor: Strategies Unlimited
EPRI Project Manager: F. Goodman, Jr.

Coal-Oil Coprocessing: Phase 1
AP-5101 Interim Report (RP2657-1); $40.00
Contractor: Hydrocarbon Research, Inc.
EPRI Project Manager: C. Kulik

A Theory on Mercury in Geothermal Fluids
AP-5111 Final Report (RP1525-6); $25
Contractor: James W. Cobble
EPRI Project Manager: V. Roberts

Mutual Solubilities and Vapor Pressures for Binary and Ternary Aqueous Systems
AP-5119 Final Report (RP1901-1); $25
Contractors: Lawrence Berkeley Laboratory; University of California at Berkeley
EPRI Project Manager: L. Atherton

COAL COMBUSTION SYSTEMS

Strategy for Fossil [Fuel] Plant Life Extension at Boston Edison Co.'s Mystic Unit 6
CS-4779 Final Report (RP2596-2); $32.50
Contractor: Boston Edison Co.
EPRI Project Managers: B. Dooley, J. Scheibel

Strategies for Fossil [Fuel] Plant Life Extension
CS-4781 Final Report (RP2596-5); $532.50
Contractors: Consumers Power Co.; Temple, Barker and Sloane, Inc.
EPRI Project Managers: D. Geraghty, B. Dooley

State-of-the-Art Maintenance and Repair Technology for Fossil [Fuel] Boilers and Related Auxiliaries
CS-4840 Final Report (RP2504-1); $550
Contractors: General Physics Corp.; Duke Power Co.
EPRI Project Manager: D. Broske

Combustion Characterization of the Kentucky No. 9 Cleaned Coals
CS-4994 Final Report (RP2425-1); $40
Contractor: Combustion Engineering, Inc.
EPRI Project Manager: A. Mehta

Effects of Cycling on Environmental Controls at Fossil [Fuel] Fired Power Plants
CS-5055 Final Report (RP1184-6); $32.50
Contractor: Bechtel Group, Inc.
EPRI Project Managers: G. Poe, E. Cichanowicz

Management of Solid By-Products From Advanced SO_2 Control Systems
CS-5076 Final Report (RP2708-1); $47.50
Contractor: ICF Northwest
EPRI Project Manager: D. Golden

Steam Turbine Blade Reliability Seminar and Workshop, 1986
CS-5085 Proceedings (RP1407-2); $62.50
Contractor: Encor-America, Inc.
EPRI Project Manager: T. McCloskey

A New Emergency Lubricating-Oil System for Steam Turbine Generators
CS-5104 Final Report (RP1648-6); $25
Contractor: General Electric Co.
EPRI Project Managers: T. McCloskey, S. Pace

Guidelines: Long-Term Layup of Fossil [Fuel] Plants
CS-5112 Final Report (RP1266-38); $25
Contractor: Florida Power & Light Co.
EPRI Project Manager: J. Scheibel

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CS-5116 Final Report (RP2422-10); $55
Contractor: Baker/TSA, Inc.
EPRI Project Manager: D. Golden

Database of Generic Chemical Additives Usage in Cooling-Water Systems
CS-5133 Final Report (RP1261-14); $250
Contractor: Utility Data Institute, Inc.
EPRI Project Manager: W. Micheletti

Spare Parts Program Practices for Flue Gas Desulfurization Systems
CS-5152 Final Report (RP2248-4); $540
Contractor: Black & Veatch Engineers-Architects
EPRI Project Managers: D. Stewart, R. Moser

Corrosion Inhibitors for FGD Systems
CS-5157 Interim Report (RP1871-10); $47.50
Contractor: LaQue Center for Corrosion Technology, Inc.
EPRI Project Manager: B. Syrett

ELECTRICAL SYSTEMS

Improved Treating Processes and Materials for New Utility Poles
EL-4675 Final Report (RP1528-1); Vol. 1, $25;
EL-4675L Final Report; Vols. 2 and 3
Contractor: Michigan Technological University
EPRI Project Manager: H. Ng

Reliability-Based Design of Transmission Line Structures
EL-4793 Final Report (RP1352-2); Vol. 1, $55; Vol. 2, $40
Contractor: Colorado State University
EPRI Project Manager: P. Lyons

Optimal Power Flow: Research and Code Development
EL-4894 Final Report (RP1724-1); $40
Contractor: ESCA Corp.
EPRI Project Manager: J. Lamont

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Contractor: McGraw-Edison Co.
EPRI Project Manager: B. Bernstein

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Contractor: Systems Control, Inc.
EPRI Project Manager: C. Frank

Display Design for Dispatch Control Centers in Electric Utilities
EL-4959 Final Report (RP2475-1); $25
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: C. Frank

Display Design for Dispatch Control Centers in Electric Utilities: Handbook
EL-4960 Final Report (RP2475-1); $15,000
Contractor: Westinghouse Research and Development Center
EPRI Project Manager: C. Frank

Nondestructive Evaluation of Wood Utility Poles
EL-5063 Interim Report (RP1352-2); Vol. 1, $32.50
Contractor: Colorado State University
EPRI Project Manager: P. Lyons

Thermal Stability of Soils Adjacent to Underground Transmission Power Cables: Phase 2
EL-5090 Final Report (RP7883-1); $32.50
Contractor: Georgia Institute of Technology
EPRI Project Manager: T. Rodenbaugh

ENERGY MANAGEMENT AND UTILIZATION

State-of-the-Art Assessment
EM-4571 Final Report (RP2478-1); $25
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EPRI Project Manager: I. Harry

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EPRI Project Manager: A. Karp

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EPRI Project Manager: C. Hiller

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Contractors: Synergic Resources Corp., Science Applications International Corp.
EPRI Project Manager: S. Hu

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EPRI Project Manager: G. Purcell

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Contractor: Burns & McDonnell Engineering Co.
EPRI Project Manager: S. Braithwait

Hydronic Heat Pumps for Residential and Light-Commercial Applications
EM-5113 Final Report (RP2033-6); Vol. 1, $25; Vol. 2, $40
Contractor: Battelle, Columbus Laboratories
EPRI Project Manager: C. Hiller

ENVIRONMENT

Status Reports on Selected Environmental Issues
EA-5097-SR Special Report (RP5002); $25
EPRI Project Manager: M. A. Allan

Status Reports on Selected Environmental Issues: Liming of Acidified Waters
EA-5097-SR Special Report (RP2661, RP5002); Vol. 1, $25
EPRI Project Manager: C. Hakkarinen

Status Reports on Selected Environmental Issues: Forest Decline—Environmental Causes
EA-5097-SR Special Report (RP2662, RP5002); Vol. 2, $25
EPRI Project Manager: C. Hakkarinen

Forest Health and Ozone
EA-5135-SR Special Report (RP2661-14); $25
EPRI Project Manager: C. Hakkarinen

Acidic Deposition: Effects on Agriculture
EA-5149 Final Report (RP1908-2); $32.50
Contractors: Oak Ridge National Laboratory; North Carolina State University
EPRI Project Manager: J. Huckabee

NUCLEAR POWER

The Reactor Analysis Support Package (RASP)
NP-4498 Final Report (RP1761-1); Vol. 6, $40
Contractor: S. Levy Inc.
EPRI Project Manager: L. Agee

Experimental Studies: Pipe Whip and Impact
NP-4534 Final Report (RP1324-5); $40
Contractors: Commissariat à l'Energie Atomique; Framatome
EPRI Project Manager: H. Tang

Once-Through Integral System (OTIS) Test Program for Babcock & Wilcox Raised-Loop Design Safety Evaluation
NP-4572 Final Report (RP2399-1); Vols. 1–4, $160
Contractor: Babcock & Wilcox Co.
EPRI Project Manager: J. Sursock

ARMP-02 Documentation
NP-4574-CCM Computer Code Manual, Part II (RP1252-10, RP1690-1); Vol. 1, $25; Vol. 2, $25; Vol. 3, $25
Contractor: GRP Consulting
EPRI Project Manager: W. Eich

IMAGE Information Monitoring and Applied Graphics Software Environment for the IBM PC
NP-4696-CCM Computer Code Manual (RP2395-6); Vol. 1, $32.50; Vol. 2, $25
Contractor: Charles P. Horne, Inc.
EPRI Project Manager: D. Cain

Methods for Ultimate Load Analysis of Concrete Containments: Second Phase
NP-4869M Interim Report (RP2172-1); $25
NP-4869SP Interim Report (RP2172-1); $6000
Contractor: Anatech International Corp.
EPRI Project Manager: H. Tang

PWR Compact Analyzer: An Interactive Simulator
NP-4930 Interim Report (RP2395-2); $32.50
Contractor: Systems Control, Inc.
EPRI Project Manager: R. Colley

Methodology for Calculating Combustible Gas Concentration in Radwaste Containers
NP-4938 Final Report (RP2558); $32.50
Contractor: Analytical Resources, Inc.
EPRI Project Manager: P. Robinson

Utility Guidelines for Reactor Noise Analysis
NP-4970 Final Report (RP2640-1); $25
Contractor: Oak Ridge National Laboratory
EPRI Project Manager: R. Colley

EPRI Operations and Maintenance Source Book
NP-4986-SR Special Report; $62.50
EPRI Project Manager: F. Gelhaus

Laboratory Evaluations of Cobalt-Free, Nickel-Based Hard-Facing Alloys for Nuclear Applications
NP-4993 Topical Report (RP1935); $25
Contractor: Velan Inc.
EPRI Project Manager: H. Ocken

Array Coil Probe
NP-5009 Final Report (RPS301-6); $25
Contractor: Combustion Engineering, Inc.
EPRI Project Managers: C. Welty, T. Oldberg

Stress Corrosion Cracking Test of Expanded Steam Generator Tubes
NP-5012 Final Report (RPS303-22); $32.50
Contractor: Foster Wheeler Development Corp.
EPRI Project Manager: A. McIlree

Hideout and Return of Chloride Salts in Heated Crevices Prototypic of Support Plates in Steam Generators
NP-5015 Topical Report (RP1171-3); $25
Contractor: Central Electricity Generating Board (England)
EPRI Project Manager: C. Shoemaker

Crevice Corrosion of Support Alloys in the Secondary Environments of Nuclear Steam Generators—Supplemental Report
NP-5017 Final Report (RP623-6); $32.50
Contractor: SRI International
EPRI Project Manager: C. Shoemaker

Seismic Ruggedness of Aged Electrical Components
NP-5024 Final Report (RP1704-4); $32.50
Contractor: Wyle Laboratories
EPRI Project Manager: G. Sliter

Guidelines for Designing Fire Protection Systems for Cable Trays
NP-5025 Final Report (RP1165-2); $25
Contractor: Impell Corp.
EPRI Project Manager: G. Sliter

Assessment of Sulfur in Chemical Cleaning of PWR Steam Generators
NP-5026 Final Report (RPS305-9); $40
Contractor: Babcock & Wilcox Co.
EPRI Project Manager: L. Williams

Causes of and Corrective Actions for Pitting in Steam Generator Tubing
NP-5037 Final Report (RPS308-3); $32.50
Contractor: Ohio State University
EPRI Project Managers: M. Angwin, P. Paine

Reactor Coolant Pump Trip Criteria and Transient Identification Technique for PWRs
NP-5039 Final Report (RP2290-3); $32.50
Contractor: EG&G Idaho, Inc.
EPRI Project Managers: J. Kim, M. Divakaruni

Calendar

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

SEPTEMBER

25
Predicting Groundwater Quality Changes and Assessing Solid-Waste Disposal/Use
Denver, Colorado
Contact: Ishwar Murarka (415) 855-2150

OCTOBER

1–2
Seminar: Electric and Magnetic Field Effects
Minneapolis, Minnesota
Contact: Bob Black (415) 855-2735

6
Predicting Groundwater Quality Changes and Assessing Solid-Waste Disposal/Use
Los Angeles, California
Contact: Ishwar Murarka (415) 855-2150

6–8
Seminar: Computerized FGD Retrofit Cost Estimating
Denver, Colorado
Contact: Paul Radcliffe (415) 855-2720

6–8
1987 Fuel Supply Seminar
Baltimore, Maryland
Contact: Jeremy Platt (415) 855-2628

6–9
1987 PCB Seminar
Kansas City, Missouri
Contact: Claudia Runge (415) 855-2149

7
Predicting Groundwater Quality Changes and Assessing Solid-Waste Disposal/Use
Dallas–Fort Worth, Texas
Contact: Ishwar Murarka (415) 855-2150

9
Predicting Groundwater Quality Changes and Assessing Solid-Waste Disposal/Use
Atlanta, Georgia
Contact: Ishwar Murarka (415) 855-2150

13–15
Conference: Effects of Coal Quality on Power Plants
Atlanta, Georgia
Contact: Arun Mehta (415) 855-2895

13–16
Workshop: Para-analytic Techniques and Applications
Chicago, Illinois
Contact: Jeremy Platt (415) 855-2628

14–16
5th International Conference on Solving Corrosion Problems
Buffalo, New York
Contact: Charles Dene (415) 855-2425
or Robert Moser (415) 855-2277

15–16
Seminar: Power Plant Water Management
Chicago, Illinois
Contact: Wayne Micheletti (415) 855-2469

20–22
Workshop: Fossil Fuel Plant Cycling
Princeton, New Jersey
Contact: Murthy Divakaruni (415) 855-2409

26–29
7th Annual Coal Gasification Contractors' Conference
Palo Alto, California
Contact: Neville Holt (415) 855-2503

26–30
Rotor Bearing Analysis Technique
Charlotte, North Carolina
Contact: Stanley Pace (415) 855-2826

27–28
Coal Markets and Utilities' Compliance Decisions
St. Louis, Missouri
Contact: Jeremy Platt (415) 855-2628

28–30
Fish Protection at Steam and Hydro Power Plants
San Francisco, California
Contact: Wayne Micheletti (415) 855-2469

NOVEMBER

5–6
6th Reactor Physics Software Users Group Meeting
Palo Alto, California
Contact: Walter Eich (415) 855-2090

10–12
Conference: Boiler Tube Failures in Fossil Fuel Plants
Atlanta, Georgia
Contact: Barry Dooley (415) 855-2458
or David Broske (415) 855-8968

17–18
8th Annual EPRI NDE Information Meeting
Palo Alto, California
Contact: Soung-Nan Liu (415) 855-2480

17–18
Regional Seminar: FGD Operations
Indianapolis, Indiana
Contact: Rob Moser (415) 855-2277

29–December 2
Fly Ash and Coal Conversion By-products
Boston, Massachusetts
Contact: Ishwar Murarka (415) 855-2150

DECEMBER

1–2
Workshop: Weld Repair of High-Pressure and Intermediate-Pressure Turbine Rotors
Palo Alto, California
Contact: Jeff Byron (415) 855-8967

1–3
Fossil Fuel Plant Retrofits for Improved Availability and Heat Rate
San Diego, California
Contact: George Touchton (415) 855-8935

2–3
Regional Seminar: FGD Operations
Dallas, Texas
Contact: Rob Moser (415) 855-2277

7–10
Seminar: Probability Methods for Generation Costing
Athens, Ohio
Contact: Jerry Delson (415) 855-2619

8–10
Seminar: Availability and Reliability of Large Turbines and Hydraulic Generators
Scottsdale, Arizona
Contact: Jim Edmonds (415) 855-2291

10–11
BENCHMARK Demonstration and Users Group Meeting
Athens, Ohio
Contact: Jerry Delson (415) 855-2619

MARCH

16–18
PWR Primary Chemistry and Radiation Field Control
Berkeley, California
Contact: Chris Wood (415) 855-2379

Authors and Articles

Young

Shula

Porcella

Ng

Huckabee

Kennon

Dalton

Pursuing the Promise of Superconductivity (page 4) surveys the electric utility applications and markets that may flow from today's Number One scientific breakthrough as it is reduced to practice in durable technology. Written by John Douglas, science writer, with input from 10 research directors and managers of EPRI's Electrical Systems, Advanced Power Systems, and Energy Management and Utilization divisions, including materials specialists of the Exploratory Research group.

Frank Young, associate director of the Electrical Systems Division, coordinated the technical guidance. Young has been with EPRI since 1975, most of the time with the Planning and Evaluation Division, where he was EPRI's manager of strategic planning from 1981 until April of this year. He was program manager for overhead transmission research when he first came to EPRI. Young was formerly with Westinghouse Electric for 20 years, eventually as manager of UHV transmission research. ■

Toxic Research and the Real World (page 16) describes EPRI research that is going beyond dose-response data to identify and understand the real-world interactions of potential pollutants. Written by Michael Shepard, *Journal* feature writer, who drew technical information from two research managers in EPRI's Environment Division.

Don Porcella, a project manager for ecological studies, focuses on the impacts of power facilities and processes on aquatic systems. At EPRI since December 1984, he was formerly with Tetra Tech for six years, where he managed analyses of lakes as cooling resources. Still earlier, he was on the civil and environmental engineering faculty at Utah State for nine years. During that time he was a visiting scientist at the EPA Environmental Research Laboratory in Oregon.

John Huckabee, manager of ecological studies since early 1985, was a project manager for six previous years, dealing with the terrestrial, aquatic, and atmospheric effects of power system operations. He came to the Institute from Oak Ridge National Laboratory, where he was an environmental sciences division researcher for eight years. ■

Developing the Next Generation of Sulfur Controls (page 22) introduces EPRI's newest R&D facility, the High-Sulfur Test Center, and its array of laboratory and pilot equipment for scaling up new coal combustion exhaust cleanup systems. Written by Ralph Whitaker, feature editor of the *Journal,* with technical assistance from the staff of EPRI's Coal Combustion Systems Division.

Stuart Dalton, manager of the Desulfurization Processes Program since 1979, had earlier experience as a project manager in the Air Quality Control Program. He came to EPRI in 1976 after four years with Pacific Gas and Electric and three years with Babcock & Wilcox. ■

Managing America's Wood Pole Inventory (page 30) reviews R&D results, some of them already in use, for gauging wood pole life more accurately, preserving poles against natural hazards, and strengthening them more economically. Written by Michael Shepard, *Journal* feature writer, with three research managers of EPRI's Electrical Systems Division.

Bill Shula, manager of the Distribution Program for nearly 10 years, has been an Institute staff member since 1976, following a year on loan to EPRI from Texas Electric Service. He was with the utility for 27 years, including 8 years in charge of distribution planning.

Harry Ng, a project manager with Shula, came to EPRI in 1983 after 12 years with Tucson Electric Power, where he was a supervising engineer in the distribution group.

Dick Kennon, manager of the Overhead Transmission Lines Program since 1978, is also responsible for EPRI's transmission line mechanical research and high-voltage test facilities. He joined EPRI in 1975 after nearly 23 years with Westinghouse Electric, ultimately as manager of capacitor equipment engineering. ■

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