High-Temperature Superconductors

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Cover: Photomicrograph of the bismuth-strontium-calcium-copper oxide material that is being pursued for high-temperature superconductor power applications. (Photo courtesy of Michael Davidson, National High Magnetic Field Laboratory, Florida State University)

HTSCs: Five Years of Progress

This year marks the fifth anniversary of the discovery of high-temperature superconductors (HTSCs). If you have been following the news coverage of this area of research in the popular press, you may have experienced what seemed like a roller coaster ride. Perceptions of this scientific discovery have ranged from the wildly enthusiastic to a view that the party was over and that these new materials would always remain a scientific curiosity.

But progress has, in fact, far exceeded realistic expectations for this remarkable discovery. While an explanation of the underlying phenomenon of high-temperature superconductivity is still not in hand, this scientific find has moved quietly into early technological development. Groups in the United States and Japan are routinely making 100-meter lengths of HTSC wire with continuous improvement in electrical and mechanical properties. Laboratory prototypes have provided proof-of-principle demonstration of several power applications, including motors, transmission cables, and fault-current limiters.

This month's cover story reports on the technological state of the new superconductors. Our goals are to provide an overview of the progress made in the past half-decade to develop these materials for use by the electric utility industry, and to highlight many of the issues that have made HTSCs such a challenge. Rather than limiting this review to EPRI-sponsored programs, we have included the most remarkable accomplishments from public and private organizations around the world.

In an earlier *EPRI Journal* article (January/February 1990), we speculated on the breadth and depth of the potential impact of these new materials in the power industry. While the degree to which high-temperature superconductors may eventually penetrate the market for large electrical equipment is still uncertain, there is no doubt that superconducting technology will establish a market presence and demand a thorough and intelligent assessment of its cost and benefits.

For those who design, manufacture, purchase, operate, or service electrical equipment, the achievements described in the current article point toward a revolutionary change in the underlying technology of the business. If today's rate of progress continues, the common assumption that we will have to wait until the next century for application of high-temperature superconductors will not prove to be correct. The time for adapting this new technology will arrive very soon. The time for influencing its development has already come.

We invite your participation and feedback in our ongoing effort to understand this exciting development and to assess its potential.

Thomas R. Schneider, Executive Scientist
Office of Exploratory & Applied Research

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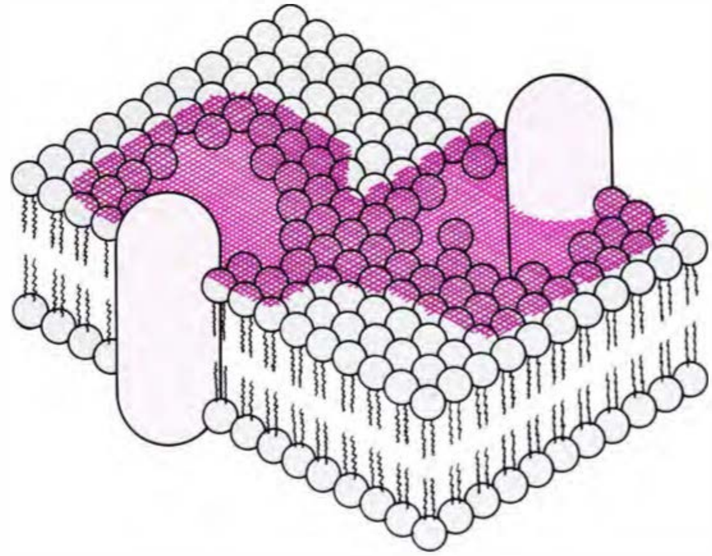

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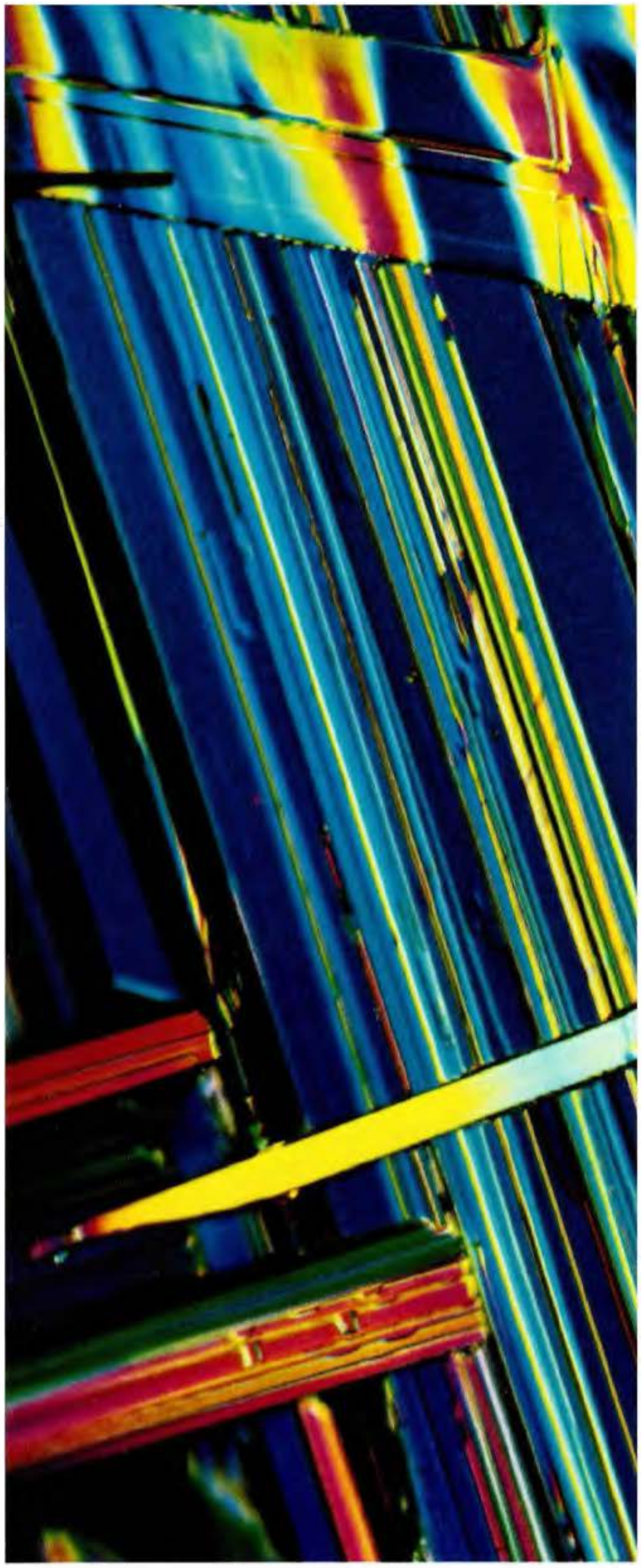


4 Superconductors

THE STORY IN BRIEF Interest in high-temperature superconductors is heating up again, as researchers make steady progress on technical problems that appeared daunting only a few years ago. Working with new materials, corporate and university laboratories are now producing short samples of wire with performance levels approaching those needed for electric power applications like advanced motors and power cables. And scientists, probing the atomic microstructure of the new superconductors ever more deeply, are learning some of the secrets that are key to overcoming such fundamental performance barriers as weak-link grain boundaries and magnetic flux creep. But even as researchers approach the promised land in material performance, there are new calls for a coordinated and more focused national program in high-temperature superconductivity that will ensure a leading position for American science and industry in the race to develop power applications.

Superconductors Are Still Hot

by Taylor Moore

A NEW WAVE OF OPTIMISM HAS SPREAD AMONG SCIENTISTS working with the new high-temperature superconductors (HTSCs), overcoming earlier fears that fundamental—perhaps insurmountable—obstacles stood in the way of ever pushing the materials' technical capabilities to the levels needed for practical use in electric power applications. Wires and tapes made from some of the new materials are approaching the electrical and mechanical requirements for use in electromagnets and conductors for prototype superconducting motors, generators, and power transmission cables. And researchers say they are confident that continued, incremental progress—not a major breakthrough—is what is needed to make commercial equipment containing high-performance HTSCs a reality by the end of the decade.

Many of the major laboratories intensively pursuing HTSCs have reported encouraging results in recent months. These include the ability to consistently make material that is durable enough to withstand processes for manufacturing useful lengths of conductor; the achievement of high critical current densities in short lengths of fabricated HTSC conductor; and the maintenance of superconductivity in some samples in the presence of a strong magnetic field at temperatures no lower than the 77 K (absolute) of inexpensive liquid nitrogen. As recently as a few years ago, the best HTSC wires were quite brittle, were capable of carrying no more current than copper, and could withstand almost no magnetic field. To many, it seemed that the promise of high-temperature superconductivity would never be realized.

Since then, however, "researchers have demonstrated that the new HTSC materials can meet all the performance requirements for electric power application, albeit not yet in the same sample," says Donald Von Dollen, a project manager in EPRI's Electrical Systems Division who manages some of the Institute's superconductivity R&D. Meanwhile, several groups are making steady strides in bulk materials processing and the manufacture of su-

Ron May

perconducting wire and tape. Low-current-density HTSC wires in continuous lengths of up to 1000 meters are already produced commercially for R&D use.

Still, recent progress notwithstanding, the technology remains high risk because material performance is only part of the challenge, notes Thomas Schneider, an executive scientist in the Office of Exploratory & Applied Research who coordinates much of EPRI's involvement in superconductivity. "The technologists are confident about achieving the performance targets. But we can't really be sure yet that if we reach the targets, we will be able to afford the product. That's the major risk at the moment—we don't know about the cost. But the technical advances are telling us that the technology is indeed feasible."

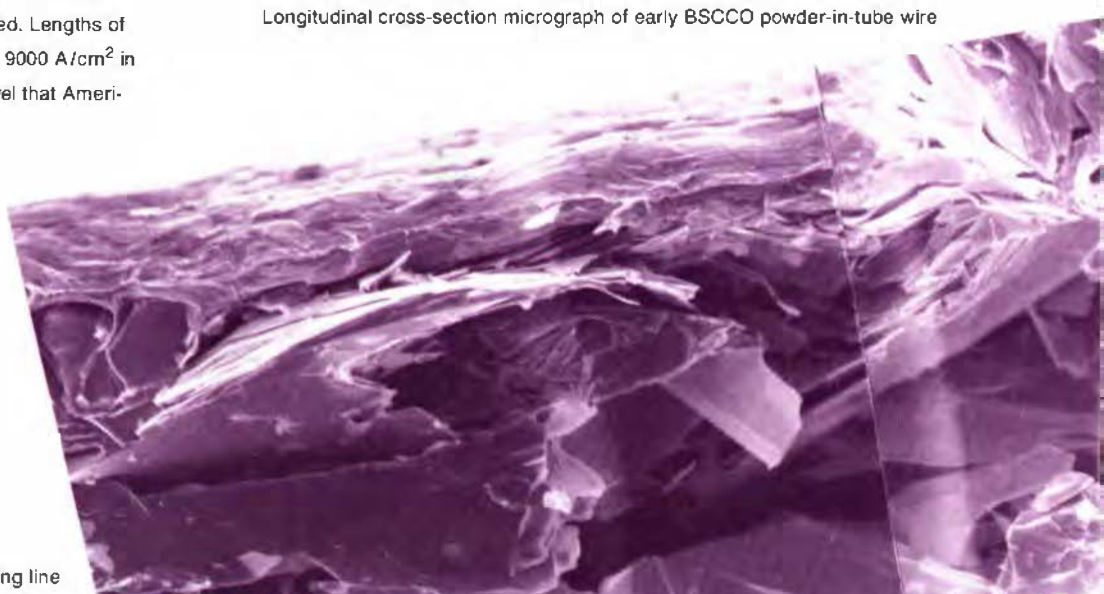
Adds Ken Goretta, an HTSC researcher at Argonne National Laboratory, one of three national laboratories with major programs in the field: "In just the last few years, I've run the gamut between optimism and utter pessimism, and I'm more optimistic now than at any time since I started. The main reason is that people have made sections of wire with good properties. The results already reported would lead all but the most skeptical person to be optimistic."

While there is renewed hope that the remaining barriers to high-performance superconductors will succumb to the persistent probing of science within the next few years, there are also concerns over which advanced industrial economies will reap the ultimate economic advantage from the new technology. Some scientists in this country worry that without a major new initiative to focus disparate (and in some cases duplicative) R&D efforts, the technology may become yet another case in which technical and market dominance is eventually ceded to non-U.S.-based firms.

"Can we support the kind of long-range research that's going to pay off in 10 years, not 3? Or will we just buy the stuff from Japan or Europe?" asks Ted Geballe, a professor emeritus of applied physics and materials science and engineering at Stanford University who is considered a senior

AMERICAN SUPERCONDUCTOR: MAKING HTSC WIRE FOR APPLICATIONS Based in Watertown, Massachusetts, American Superconductor Corporation is one of several U.S. firms developing high-temperature superconducting wire for use in electric power applications. The company is producing flexible wire and tape with a bismuth-based compound, using a proprietary version of the powder-in-tube method, in which HTSC materials are annealed at high temperature within a silver sheathing and then pressed or rolled. Lengths of wire as long as 60 meters can carry over 9000 A/cm^2 in zero applied magnetic field, a current level that American Superconductor says can be used in developmental application prototypes. The company has formed strategic alliances with a number of commercial partners and recently announced a collaborative venture with key national laboratory and university HTSC research centers.

Longitudinal cross-section micrograph of early BSCCO powder-in-tube wire



Wire is rolled and wound in pilot manufacturing line

statesman of superconductivity research. "If we go along haphazardly, without co-ordination, I don't think we'll get there as fast as our foreign competition."

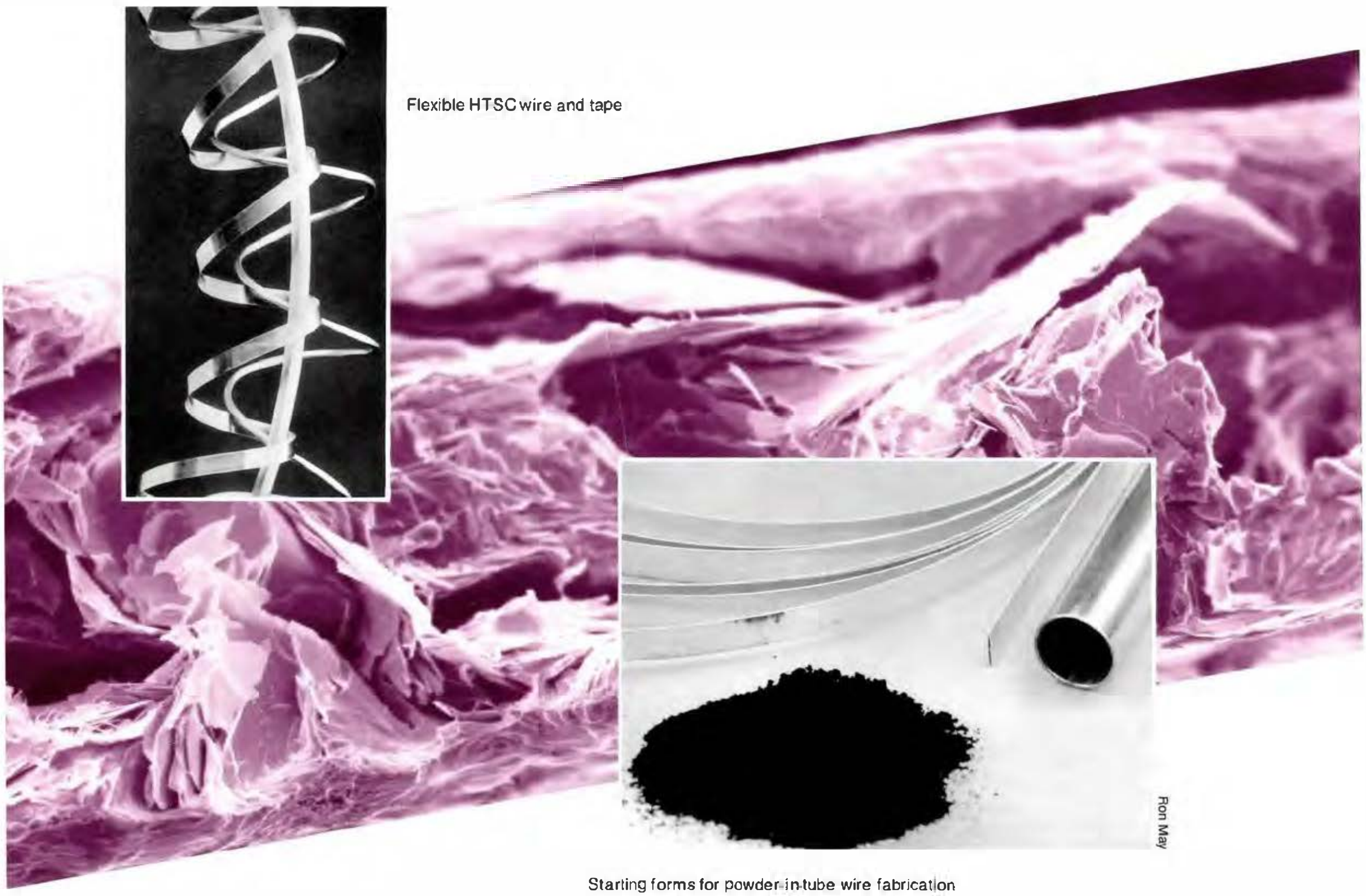
Realities dampened initial euphoria

When scientists around the world began in late 1986 to confirm reports of superconductivity at unprecedentedly high temperatures in an obscure class of ceramic oxides, both the popular and scientific media could hardly contain their euphoria. Long-sought visions of superefficient generators and motors and very-low-loss power lines, as well as magnetically levitated, high-speed trains and giant magnetic energy storage coils, suddenly seemed within the realm of commercial viability. Perceptions that these visions would be rapidly realized were seemingly made unanimous by the discovery, in 1987, of an yttrium-barium-copper oxide (YBCO) that changed to a zero-resistance, superconducting state when cooled to the relatively balmy absolute temperature of 92 K. Although that is still –294° on the Fahrenheit scale, it is well above the 77 K (–320°F) boiling point of nitrogen.

These discoveries triggered a frenzied series of crash programs in government and corporate laboratories worldwide and sparked major national and industry research initiatives here and abroad. Many of the efforts in this country have received active participation and support from EPRI on behalf of its electric utility members. Most continue to this day, although with somewhat less government and industry funding than was available at the period of peak national interest.

There have been significant strides in critical transition temperature, a key parameter of interest in superconductivity (although not the only important one). In 1988 the highest reported value rose to 125 K; that temperature—obtained for a thallium-based compound—has yet to be exceeded.

Some scientists are still searching for signs of superconductivity at higher temperatures. Paul Chu of the University of Houston, one of the codiscoverers of superconductivity in the YBCO compound



Flexible HTSC wire and tape

Starting forms for powder-in-tube wire fabrication

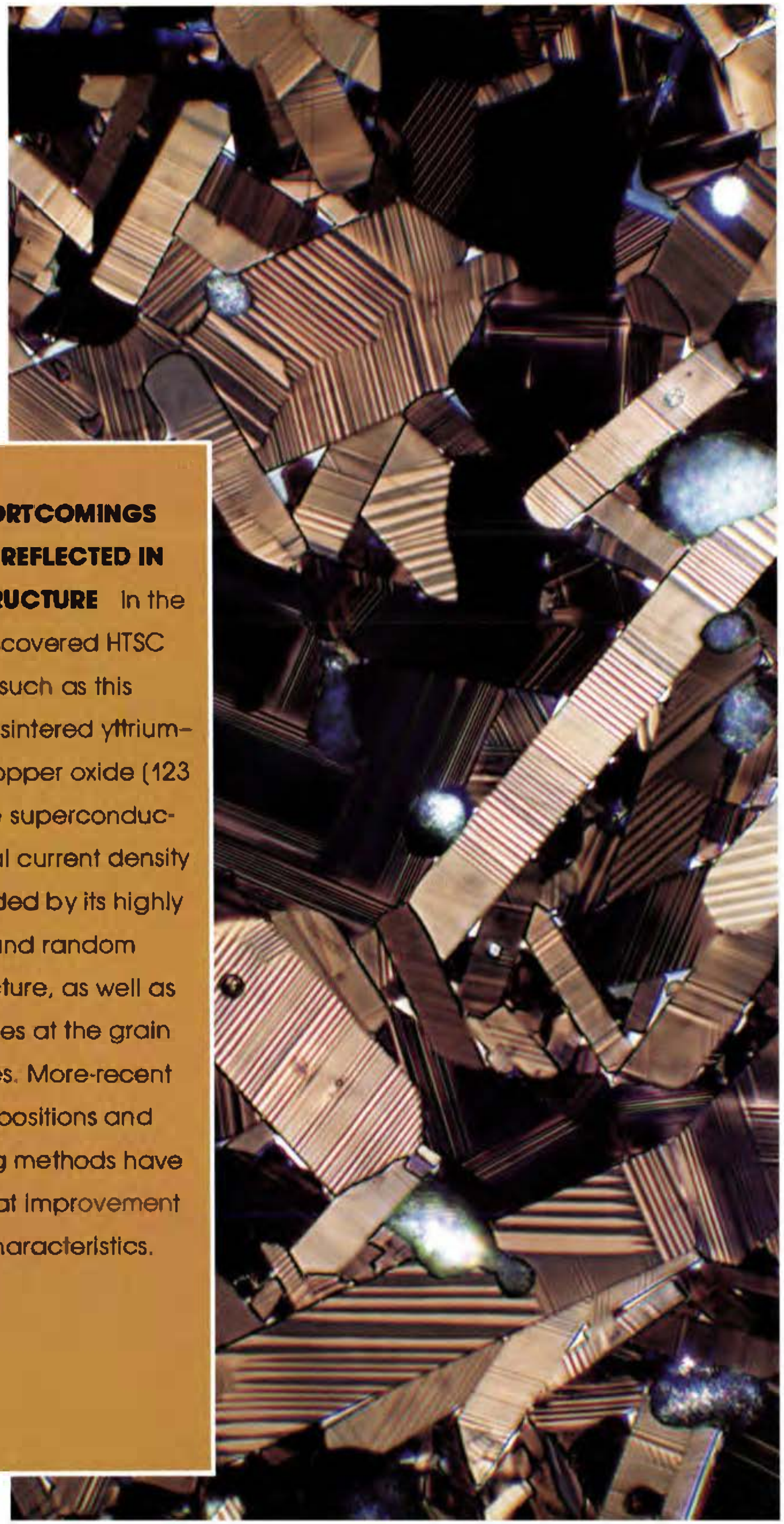
Ron May

that is the most widely studied HTSC material, remains convinced that "the possibility of the discovery of a superconductor at room temperature is as strong as ever." Meanwhile, some researchers have shifted their attention to the other two parameters that are key to eventual power applications—critical current density and critical magnetic field—and are seeking to increase their values in known superconductors.

Despite the early advances, by 1989 the difficult realities and fundamental challenges hit home among scientists who were trying to work out the physics and chemistry of these exotic, potentially revolutionary new materials well in advance of reaching a theoretical understanding of the mechanism of high-temperature superconductivity. The downturn in the mood of many researchers and the change in their outlook for near-term success were reflected in several gloomy reviews, including an article in *Science* that asked pointedly, "Is the party over?"

The pessimism reflected daunting practical problems on several fronts. Besides being brittle and having rather poor magnetic properties, the earliest compounds were chemically unstable, tending to steal copper and oxygen from any nearby source and thereby ruining the material's superconductivity. Researchers have since learned which compositions are stable, but controlling the amount of copper remains a challenge. Moreover, HTSC wire must be sheathed in a good conventional conductor so that it isn't damaged by current if it suddenly becomes nonsuperconducting. Because almost any other material will react with the HTSC material under high-temperature processing, a popular approach is to insert HTSC powder into tubes of pure silver, which are then annealed and rolled or pressed into tape or drawn into wire. A major challenge in manufacturing HTSC conductors is to come up with an alternative to silver that offers fewer processing difficulties and lower cost.

So far, researchers have found three major families of HTSC materials, all of which feature layers or planes of copper oxide weakly coupled in a crystal lattice atomic structure with other layers of some combination of elements, either yttrium-barium, thallium-barium, or bismuth-strontium. But only certain chemical composi-



Photomicrograph courtesy of Oak Ridge National Laboratory, Superconducting Technology Program

EARLY SHORTCOMINGS OF HTSCS REFLECTED IN MICROSTRUCTURE In the earliest discovered HTSC materials, such as this sample of sintered yttrium–barium–copper oxide (123 YBCO), the superconductor's critical current density was impeded by its highly granular and random grain structure, as well as by impurities at the grain boundaries. More-recent HTSC compositions and processing methods have led to great improvement in these characteristics.

tions within the families are superconducting, and some exhibit much higher critical transition temperatures, current densities, and magnetic fields than others. Obtaining just the right combination by fine-tuning the processing conditions is as much a laboratory chef's art as science. Reproducibly measuring good performance in multiple samples is yet another matter.

Moreover, the HTSC materials are generally not equally superconducting in all directions within a sample. The copper oxide planes are believed to be the region of strong superconductivity, with current flowing more easily along an axis parallel rather than perpendicular to these planes. Such two-dimensional, anisotropic superconductivity may be tolerable for thin-film electronic applications, for which useful devices can be made from single crystals with very good electromagnetic properties; indeed, thin-film electronic switches and sensors are likely to be among the earliest commercial applications of HTSCs. But flexible wire for use in high-power applications demands good properties in bulk, polycrystalline material.

As might be expected, the highest values yet reported in each of the HTSC families have been in samples measuring a few centimeters square and a few micrometers or less in depth. Critical current density for highly oriented, single-crystal thin films of yttrium-barium-copper oxide has been found to be as high as 5 million amperes per square centimeter of cross-sectional area at 77 K, and as high as 50 million A/cm^2 at liquid helium temperature (4.2 K). In late 1991, General Electric reported world-record critical current densities for a polycrystalline thick film (3 micrometers) of thallium-barium-calcium-copper oxide (TBCCO): 500,000 A/cm^2 at 4.2 K and 100,000 A/cm^2 at 82 K. But each of these results was achieved in relatively small samples and in the absence of an applied magnetic field.

In contrast, power applications of HTSCs typically require a current density of 100,000 A/cm^2 in the bulk superconductor. Depending on the application, the superconductor also must operate within a strong magnetic field. HTSC power transmission cables with adequate current-carrying capacity at 77 K would operate in a low magnetic field. But motors and generators containing electromagnets wound from HTSC wire must maintain superconductivity at such current levels while operating within powerful self-generated fields of at least several tesla. Researchers believe that it may be more practical to operate the HTSCs in such devices at temperatures around 20-35 K with nonliquid helium cooling. If superconductors could produce much higher magnetic fields—up to 18 tesla—then advanced, ultracompact generators and energy storage devices would be possible. Even higher fields could be employed for certain advanced magnetic materials processing technologies.

Because the magnetic field produced by a superconductor is intimately related to its critical current density, the current-carrying capacity of electromagnets wound from HTSC wire becomes limited by the self-generated field. Another fact related to current flow (unfortunately, for the HTSCs) is that a material's critical magnetic field is also anisotropic: higher when oriented parallel to the crystal plane, but much lower when unfavorably applied across it. For high-power-magnet applications, bulk HTSCs must withstand consistently high critical fields in all three dimensions.

The critical current density of General Electric's TBCCO thick film declines to 10,000 A/cm^2 at 65 K in a 2-tesla field in the most unfavorable orientation. Short samples of YBCO conductor a few centimeters in length, made by CPS Superconductor, reportedly can carry 100,000 A/cm^2 in zero field at 77 K but can carry only about a fifth of that level—20,000 A/cm^2—in an 8-tesla field. And the process used to make such samples is limited to a few millimeters per hour. Despite considerable progress elsewhere on the processing and manufacturing front, longer lengths of conductor, made from bismuth-strontium-calcium-copper oxide (BSCCO), still have much lower current densities. Nevertheless, researchers note, these are among several technical milestones that many observers would have considered impossible a little over two years ago. Short wires and tapes with these levels of critical current density can now be made by several processes and can satisfy the requirements for use in certain specialized electric power applications and in prototype development.

"If you know how to process the materials correctly into usable wire—and we have spent a lot of time developing proprietary technology to do just that—then you already have materials that are sufficient to meet the demands of the applications for the immediate future," says Gregory Yurek, president of American Superconductor Corporation, one of the leading U.S. firms developing superconductors for electric power uses. Established by former members of the faculty of the Massachusetts Institute of Technology, American Superconductor is already making flexible, high-quality superconducting wire and tape in a pilot manufacturing line, using its own version of the process involving powder in silver tubes. The company has formed strategic business alliances with Inco Alloys International and Pirelli Cable Corporation to develop HTSC applications.

Yurek, a former MIT professor of materials science and engineering, says 60-meter lengths of American Superconductor's wire are now showing 9000 A/cm^2 at 77 K in zero field. "That kind of material is pretty exciting. Its electrical and mechanical properties are sufficient to enable a broad range of prototype development for applications. We're at the stage now where customers can begin to use this wire—whether for motors, transmission lines, or small energy storage devices—while American Superconductor continues to make concurrent progress in both the materials science and the manufacturing engineering. I think we will start to see commercial products with components made from these materials out among end users in the second half of the decade."

Indeed, a coil made from American Superconductor's wire, which is based on a BSCCO compound, was used last year in a 25-watt demonstration motor engineered by Reliance Electric under an EPRI contract. One-half ampere of current in the superconducting field winding, immersed in a liquid nitrogen bath, drove the first known HTSC motor with a usable power output, about equal to that of a desktop computer's cooling fan.

Grain boundaries and flux-creep demons

Much of the earlier pessimism about achieving practical HTSCs stemmed from two shortcomings observed in the so-called 123 YBCO material. Unlike the excellent low-temperature superconductors (LTSCs) that are based on niobium-titanium or niobium-tin and that require costly liquid helium cooling, the ceramic YBCO material is electromagnetically granular, tending to subdivide along individual crystal grain boundaries into regions of strong superconductivity separated by interfaces with poor superconductivity. Because of this weak-link problem, the critical current density measured over useful lengths of material is typically much less than that of individual grains. The practical current density is even less when HTSC wires are wound into coils that generate strong magnetic fields.

Strong magnetic flux pinning is another virtue of LTSCs that HTSCs lack at the high temperatures at which engineers would prefer to use them. With LTSCs, which are used to make powerful electromagnets for such things as particle accelerators and magnetic resonance imaging systems, the magnetic flux lines penetrate the material and become pinned at the sites of local perturbations or defects in the atomic structure. Current flowing through the material creates a force that pushes against the flux lattice. The flux then tends to creep from these pinning sites, in turn creating some resistance (i.e., energy loss), which is antithetical to a superconductor.

For LTSCs, the temperature at which the magnetic flux lines begin to become depinned is almost identical to the materials' critical transition temperature (the level at which they become superconducting). But given the much higher thermal energy associated with the higher transition temperatures of HTSCs, flux lines become depinned more easily. And with YBCO, the atomic-level perturbations that make good pinning sites in LTSCs are instead concentrated around grain boundaries—thus impeding a high critical current density.

"Weak links at the grain boundaries and weak magnetic flux pinning combined with strong flux creep are the two principal difficulties with HTSCs," says David Larbalestier, a professor of materials science and physics at the University of Wisconsin and the director of the school's Applied Superconductivity Center. "An anisotropic but still three-dimensional material like YBCO tends to be granular with weak links and thus has much lower effective transport current density than is achieved in individual grains. If it's really only two-dimensional—as are the bismuth and thallium 2212 and 2223 phases—it appears to be possible to make the material so it is not granular, but then the flux pinning is weak. So even if a material is not granular, the critical current density can still be low because of poor flux pinning rather than granular weak links."

For reasons that are not yet entirely clear, experts say, the BSCCO compounds have shown much higher critical transport current densities across multiple grain boundaries than the YBCO materials have. One BSCCO phase, the 2223 material, is a known superconductor at 110 K.

Sumitomo Electric Industries of Japan has reported measuring 9700 A/cm^2 at 77 K and zero field in 114-meter lengths of 2223 BSCCO tape made by the powder-in-tube method. In the United States, several groups—American Superconductor, Argonne National Laboratory, Intermagnetics General, Los Alamos National Laboratory, and the University of Wisconsin—have also fabricated BSCCO powder-in-tube tapes that have demonstrated good performance at 77 K, again mostly in zero field. The current-carrying capacities in such reported results are within the range required for prototype development for power transmission applications.

At liquid helium temperature (4 K), wires made from the 2212 BSCCO compound by Japan's National Research Institute of Metals (one of several early groups to work with the BSCCO family) have demonstrated a higher current-carrying capacity than even commercially available niobium-based LTSC wires in fields exceeding 18 tesla. Researchers in Germany working for a unit of Siemens and scientists at American Superconductor have achieved similar performance. According to some experts, these results suggest that the first high-power application of HTSCs may be in hybrid, niobium-titanium-BSCCO magnets for laboratory experiments—magnets that operate at 4 K but that can produce very high magnetic fields.

One proposed model to explain why the current-carrying capacity of BSCCO exceeds YBCO's across multiple grain boundaries is that the bismuth compounds readily cleave, like mica, into platelike grains along the bismuth oxide layers; these grains tend to be well-aligned and connected, like brickwork, which promotes good current transport between them. Detailed study and measurement of single crystals have thus far been limited to the phase (2212) with a lower critical transition temperature (80–90 K). BSCCO wires and tapes are made up more of randomly oriented polycrystalline material than of single crystals and therefore have lower current densities, but experts say that certain processing methods, such as rolling, may actually help to align the grains.

Much of the renewed bullishness among HTSC researchers springs from the good results that are being reported with BSCCO, as more research groups and companies such as American Superconductor and Intermagnetics General set their sights on commercial-scale production of BSCCO wire and tape. Sumitomo, which is said to have more scientists working on HTSCs than any other group in the world, has used its BSCCO wire to make a coil capable of generating a 1-tesla field when cooled to 4 K with liquid helium. And Sumitomo is believed to be close to generating an equally strong field with such a coil at liquid nitrogen temperature.

"Many of the results that Sumitomo has reported are very impressive from a technological standpoint," says Larbalestier of the Wisconsin Applied Superconductivity Center, "but the continued development

Photomicrograph courtesy of Michael Davidson, National High Magnetic Field Laboratory, Florida State University

BISMUTH MATERIAL SHOWS IMPROVED CRYSTAL STRUCTURE The highly oriented, platelike crystal structure of a superconducting bismuth–strontium–calcium–copper oxide is seen in this reflected differential interference photomicrograph of the *ab* plane surface. The compound is known as 2212 BSCCO and has a superconducting transition temperature of 80–90 K. Some wire samples made from the compound have demonstrated better current-carrying capacity in very high magnetic fields than the more conventional, niobium-based low-temperature superconductors.

that is needed for long coil lengths of high-critical-current-density wire has to be underpinned by a scientific understanding of how to control the 2223 phase formation into well-aligned grains with good current transport.

"BSCCO is so complicated that nobody really has it under control," adds Larbalestier. "No one has yet been able to make completely aligned, pure 2223 phase. There is much debate over the correct composition needed to obtain such a phase and much uncertainty about the optimum high-temperature processing conditions. Some people think the BSCCO mixture has to become slightly liquid to get a pure phase."

Moreover, Larbalestier explains, the BSCCO materials are even more anisotropic than YBCO. And they are more vulnerable to magnetic flux creep and lattice melting. "There is much concern that they cannot maintain strong flux pinning at temperatures above 30 K, but we should remember that these materials are terrifically complicated. There is still no general agreement on the physical mechanism responsible for HTSCs," he says. "The thallium compounds are even more complicated than bismuth, but there is one phase in particular—the 1223 material—that does seem to have strong flux pinning well above the liquid nitrogen temperature. The downside is that, so far at least, the bulk material seems to be granular—if not to the same extent as YBCO, then comparably so." According to Larbalestier, "General conclusions about the long-term potential of the yttrium, bismuth, and thallium materials at 77 K are not yet justified. Should we concentrate on solving the granular problem in YBCO or thallium-1223, or the flux pinning problems of the bismuth compounds and thallium-2212/2223? The answer is not at all clear yet. Progress so far has largely been empirical. The challenge now is to understand these exceedingly complex materials, with which so much progress has been made since 1989."

Gathering momentum for applications

Assuming that the recent rate of progress in establishing sustainable electromagnetic properties and in conductor development continues, as many HTSC insiders believe it will, support is growing in this country for the next big push toward realizing the promise of high-temperature superconductivity for power equipment. Many experts believe that the materials and manufacturing technology is well enough in hand to begin to go beyond proof-of-concept application demonstrations—such as the several small HTSC motors that have been made—and to start designing and fabricating superconducting components for larger machines and for transmission cables.

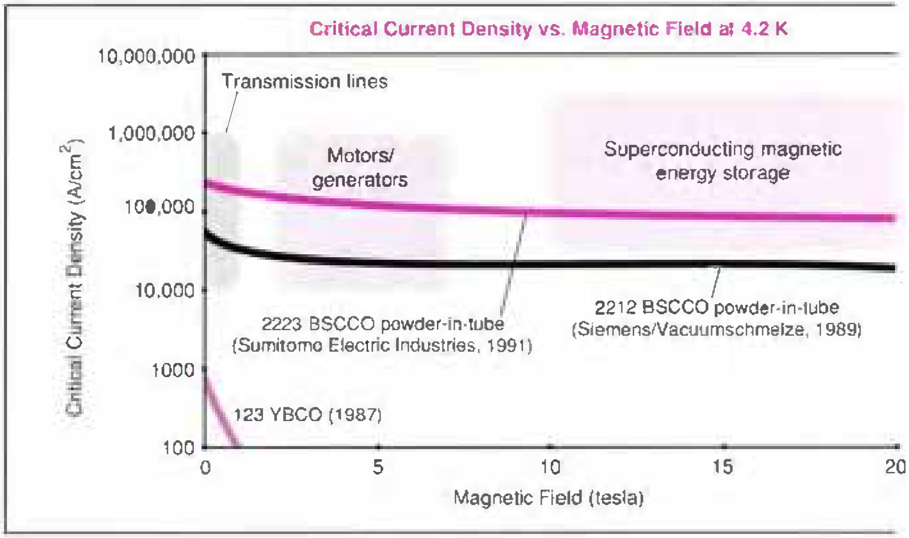
Such was the message last year from a high-level, ad hoc industry working group of more than two dozen organizations active in HTSC R&D, writing in a report requested by the undersecretary of commerce for technology, Robert White. The group, which included EPRI, noted that most federal funding for HTSC research—which this year amounts to around $150 million—is currently parceled out among numerous centers for basic science and technology and among groups focused on defense-related applications in electronics and computers. The development and scale-up of more-commercial but capital-intensive applications such as motors, generators, and cables will not happen without a major government-industry initiative. Such a program could cost $250 million and take five years to complete, the group said. So far, however, national research priorities and funding levels have not been reprogrammed along those lines.

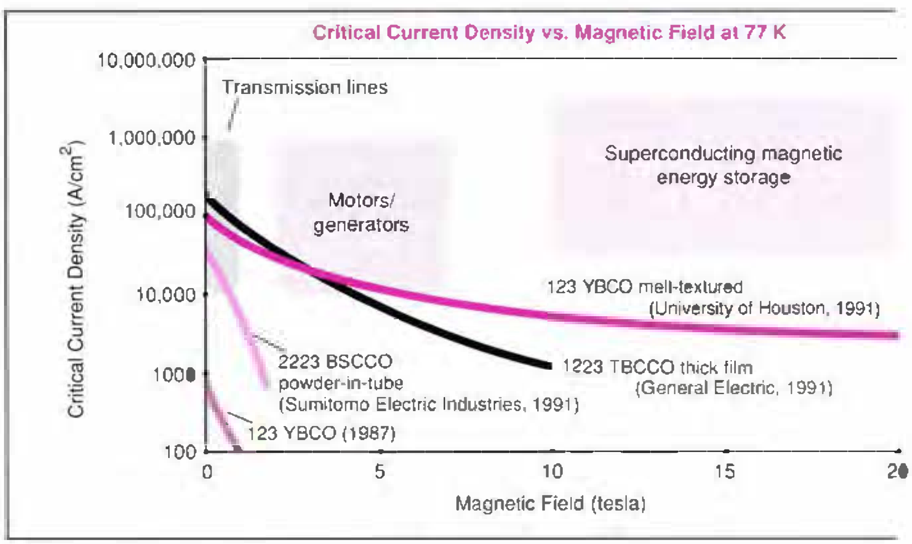
Applications-related work sponsored by EPRI and others has been ongoing virtually since the discovery of HTSCs. Although the levels of support have remained fairly low, the work has established the technical feasibility of the major applications of interest to the electric power industry; it has also established technical and economic criteria against which to gauge progress in conductor performance. As conductors progressively improve in current density and therefore in current-carrying and field-generating capacity, it will become possible to develop increasingly more powerful, yet more compact, motors.

Moreover, with current densities at least an order of magnitude higher than those

HTSC CURRENT DENSITIES AT TWO KEY TEMPERATURES

LIQUID HELIUM TEMPERATURE Reports of steady progress in raising critical current densities keep coming from HTSC research groups around the world. The shaded regions in the graphs indicate target values of current density and magnetic field for key electric power applications. When short samples of wire made from some HTSC materials are cooled to the 4.2 K absolute temperature realm of liquid helium and operated in high magnetic fields, their current-carrying capacity exceeds even that of conventional low-temperature superconductors (LTSCs). Experts say some of the earliest applications of HTSCs may be in combination with niobium-based LTSCs in hybrid electromagnets for use in research laboratories and particle accelerators.





LIQUID NITROGEN TEMPERATURE For most electric power applications, HTSCs should demonstrate high current densities in the 65-80 K temperature realm of more practical and affordable liquid nitrogen cooling. At 77 K, laboratory samples of HTSC wires and films have demonstrated good current densities. Results in some cases fall within the range required for some power applications, but the values decline with increasing magnetic field. At high fields, such as would be associated with electromagnets in large motors, generators, and energy storage coils, current densities an order of magnitude higher than presently achieved are needed. Recent progress gives researchers reason to believe that such performance levels can be reached.

presently attainable with BSCCO tapes, researchers expect to be able to reduce—also by an order of magnitude—the so-called hysteretic losses at the surface of a superconductor. These are the product of a small but inherent resistance created by induced surface currents in superconductors used in alternating-current applications, such as those that are of interest to utilities. (The famed zero-resistance property of superconductors applies only to direct current.)

Superconducting motors with higher power density and greater efficiency than conventional motors could become a major application of HTSCs, since motors now account for nearly two-thirds of all the electricity used in the United States. A design study done for EPRI by Reliance Electric indicates that the operating cost savings from a 10,000-hp HTSC motor, as compared with a conventional induction motor, could equal as much as two times the HTSC motor's estimated capital cost over its projected 30-year operating life. (In addition to building the 25-watt demonstration motor with American Superconductor's BSCCO-wire coil, Reliance Electric has made, with EPRI support, a dc motor that operates at nearly 1300 revolutions per minute [rpm] with a 75-turn YBCO solenoid winding supplied by Argonne National Laboratory.)

Oak Ridge National Laboratory has developed an axial-gap superconducting motor with an adjustable-speed drive that will serve as a prototype for future motor development and for testing the performance of new HTSC conductors as they become available. EPRI is supporting this effort as well. The axial-gap motor features a simplified design for easier manufacture and early commercialization. It has a stationary stator and field coil, eliminating the need for high-current brushes and rotating seals. Outfitted with LTSC wire-wound components, the motor has performed to design specifications in preliminary testing, delivering 102 newton-meters with a magnet current of 2100 amperes.

Meanwhile, Emerson Electric has used trapped-field superconducting disks, developed by EPRI-sponsored researchers at the University of Houston, to power the first entirely self-contained superconducting motor. The design is based on a 1979 patent issued to EPRI scientist Mario Rabinowitz that describes the trapping or storing of a powerful magnetic field in a superconducting bulk material. Disks made from YBCO material that are capable of trapping a 1.5-tesla field at 77 K have been produced at the University of Houston. "This development will have a major impact on electric energy storage and generation in the future," says the university's Paul Chu, director of the Texas Center for Superconductivity there.

Other applications of HTSCs in motors are considered feasible for development within the same time scale as the motors themselves. For example, HTSC machines could feature—in addition to their rotor windings—powerful, floating electromagnetic bearings that produce no friction to cause wear. Researchers at the University of Houston have made YBCO-based magnetic bearings that can operate at 135,000 rpm and others that can lift 60 pounds per square inch.

The inverters, or controllers, that account for 1% of all the energy used by motors may feature high-power, superconducting electronic field-effect current switches that offer far more precise control of motor speed. Researchers at the University of Maryland are working on HTSC switches based on the field-effect phenomenon, which they were the first to observe.

When made into multifilamentary wire and bundled into cables that are enclosed in underground refrigerated pipes, high-temperature superconducting cables will be able to carry more current than conventional cables in the same space, even considering the requirements for the coolant and associated refrigeration systems. Underground Systems, Inc.—an Armonk, New York, firm contracted by EPRI to study the feasibility of retrofitting existing power transmission systems with HTSCs—figures that such cables could carry as much current as conventional ones do now, but with only 1% of the conductor crosssectional area. And if the materials can achieve high enough current densities, HTSC circuits can definitely transmit power with lower losses than today's technology, even taking into account the energy for cooling.

Researchers at Underground Systems have developed technical specifications for HTSC conductors in three-phase ac power cables. These include the ability to transport at least 1500 A rms at 75 K (pumped liquid nitrogen refrigeration), with total electrical losses of no more than 0.5 watt per phase per meter, and at least 2000 A rms at 77 K, with losses of no more than 1 watt per phase per meter. The conductor assembly, round with a hollow core 2–5 cm in diameter, must also have sufficient strength to withstand manufacturing, installation, and temperature-cycling stresses and maintain performance specifications.

Underground Systems has identified 750 underground circuits in this country, each at least a mile long, as candidates for HTSC conductors that meet such specifications. The earliest, largest-payoff retrofits could increase the power ratings possible through existing pipes by a factor of 2 to 5. Over the long term, the higher power transmission capacities possible with HTSCs may stimulate new projects offering alternatives to overhead transmission lines. Recently, Pirelli Cable joined Underground Systems in an EPRI project to develop a commercially viable HTSC cable design.

Eyes on the prize

Despite the steady stream of promising results from laboratories and scientific conferences, EPRI and others whose interest in electric power applications of HTSCs is paramount must at times swim against the tide to maintain the technology's place among national priorities at a time of shrinking resources and dwindling support for R&D. Because of the depth of the technology's potential impact on industrial economies in the next century, questions about the national identities and associations of the leading minds and organizations pursuing HTSCs involve more than friendly competition. Many observers view HTSCs as one of the critical technologies for American industry in the

American Superconductor

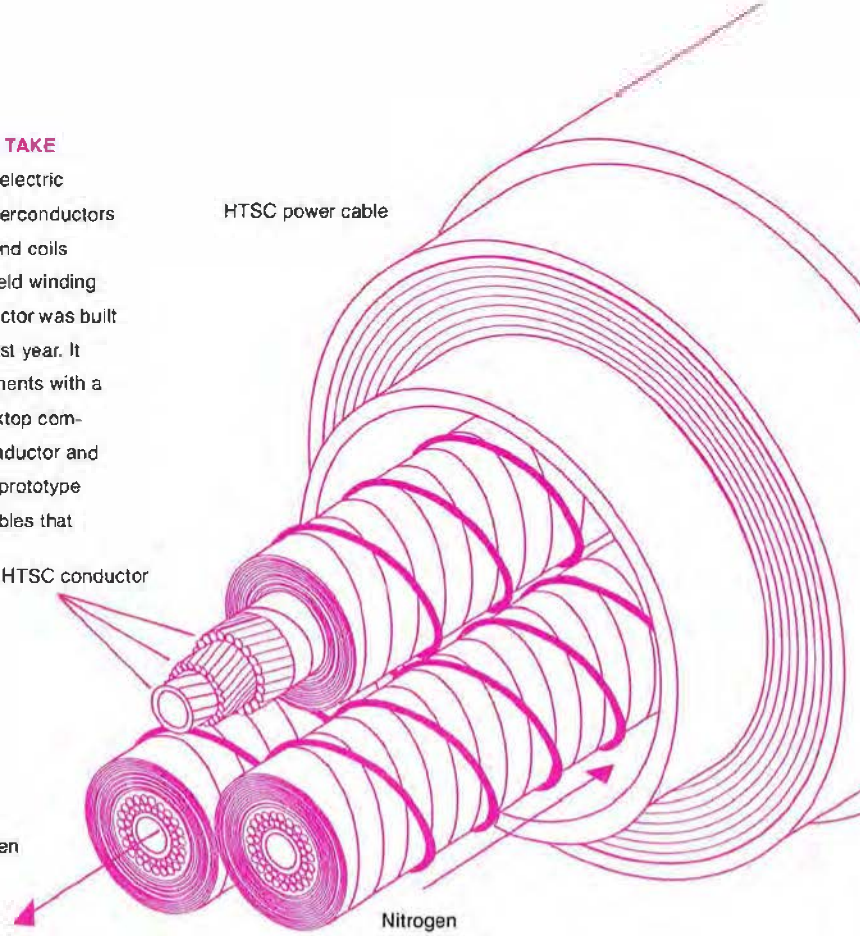
Technician removes HTSC coil from liquid nitrogen bath for testing

years ahead and feel that success could spell the difference between increasing global competitiveness and watching from the sidelines.

"The United States is a major player, but not the only player, in high-temperature superconductivity," says EPRI's Thomas Schneider. "With the progress that has occurred over the last two years, this country clearly could be left behind unless we recognize the change that has occurred and shift our national strategy—from one of pursuing the science in the hope of making another breakthrough, to one of creating an organized response and really working to move the wire and applications technology out of the laboratory and into development."

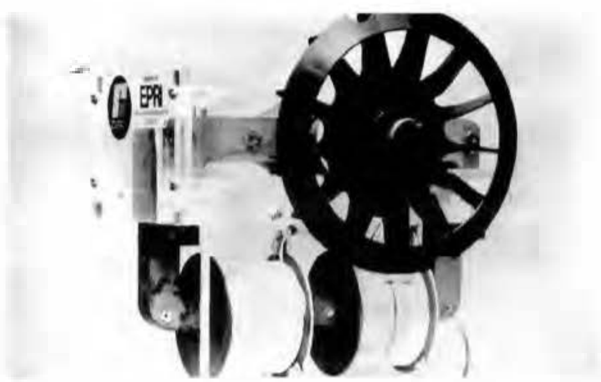
Examples of that type of response are already taking shape. In February, American Superconductor announced the formation of the Wire Development Group, a collaboration involving government, industry, and academic research organizations to develop HTSC wire for electric power applications. Joining the company in the effort are the three major national laboratory superconductivity pilot centers—at Argonne, Oak Ridge, and Los Alamos—as well as the University of Wisconsin's Applied Superconductivity Center (whose program is supported by EPRI and the Defense Advanced Research Projects Agency). The goal is to accelerate the technological developments needed to make flexible HTSC wire in lengths long enough for use in industry programs to develop commercial products. More recently, a similar joint project to develop

HTSC POWER APPLICATIONS BEGIN TO TAKE FORM Demonstrations and prototypes of electric power applications of high-temperature superconductors have begun to take shape as HTSC wires and coils become available. A 25-watt motor with a field winding made with wire from American Superconductor was built by Reliance Electric under EPRI contract last year. It was the first such motor with HTSC components with a usable power output—enough to run a desktop computer's fan. Meanwhile, American Superconductor and Pirelli Cable Corporation have fabricated a prototype HTSC conductor for power transmission cables that features a hollow center for liquid nitrogen refrigerant. Researchers at the University of Houston's Texas Center for Superconductivity, sponsored in part by EPRI, have made frictionless superconducting magnetic bearings for use in HTSC generators.




Prototype HTSC conductor

Frictionless magnetic bearings



Reliance Electric's HTSC demonstration motor

HTSC wire was announced by Intermagnetics General and Argonne.

"Wire development is the key to capturing the economic potential of high-temperature superconductivity," says Jim Daley, manager of superconductivity at the Department of Energy, which oversees the national laboratories. "Capturing scientific innovation and moving it from the mind to the marketplace requires close coordination between the public and private sectors. The countries that learn to do this effectively will have a lasting edge in international markets."

Yet realizing the promise of high-temperature superconductivity in electric power systems remains a tall order. "Although U.S. private industry acknowledges the potential market value of superconductors, it is reluctant to invest because of the high cost of research, uncertain profits, and the long-term commitment required for a return on investment in a technology that will not reach the market for at least several more years," notes EPRI's Schneider. "The United States does have the talent and facilities necessary to develop HTSCs for energy applications, but without prompt action, our opportunity to be a world leader in the technology could be lost. The time to shift our strategy is now. A strong industry-government partnership can succeed. What we need is the courage to proceed." ■

Background information for this article was provided by Thomas Schneider, Office of Exploratory & Applied Research, and Donald Von Dollen, Electrical Systems Division.

by John Douglas

THE STORY IN BRIEF

Electrical burns produced by strong electric shocks are particularly harrowing injuries. Damage to skin and muscle tissue is typically progressive, often moving far beyond the original burn area and resulting in the eventual loss of entire limbs. Researchers working under EPRI contract have now discovered the mechanisms underlying this tissue damage: electric fields produced by the shock current as it travels through the body cause hidden damage to cell membranes along the way. This knowledge has led not only to the development of new diagnostic equipment but also to a breakthrough therapeutic treatment that appears to halt progressive tissue damage from shock injuries. Clinical trials for the therapy will be conducted next year at the newly established Electrical Trauma Center, located at the University of Chicago.

MAJOR ELECTRICAL INJURY RANKS AMONG THE MOST DEVASTATING FORMS OF TRAUMA: up to 75% of patients hospitalized for direct high-voltage electrical contact lose at least one limb, and fewer than 15% recover sufficiently to return to work. Until recently, two important factors have hampered effective treatment. First, the full extent of injury often has not been readily apparent, the result being a disheartening series of progressively more extensive amputations as initially healthy-looking tissue succumbs to hidden damage. Second, the fundamental nature of electrically induced damage at the cellular level has not been understood, so no specific therapies have been available to reduce or reverse the process.

Now research by Dr. Raphael Lee and his colleagues at the University of Chicago, with funding from EPRI and several other sponsors, has led to the development of both new diagnostic techniques for determining the true extent of electrical injury and a promising new drug therapy that may be able to minimize post-electric-shock cell degeneration. The key to both of these accomplishments is the discovery that electrical "burns" involve not just thermal injury caused by the passage of current through living tissue, as was previously thought. Rather, much of the damage results from the structural breakdown of cell membranes due to the presence of strong electric fields established within the membranes during electric shock. The new drug therapy aims specifically at fostering membrane repair.

To apply such innovative treatments for electrical injuries as they become available, the University of Chicago Hospitals have established the Electrical Trauma Center, the nation's first such center. It includes eight specially equipped intensive care rooms, to which victims of high-voltage electric shock can be airlifted from virtually anywhere in the United States within a critical 6-hour intervention period. Several advanced medical imaging technologies will soon be ready for bedside use in the center to diagnose the extent of injury and monitor recovery, and clinical trials of the new drug therapy are expected to begin next year. Already, utilities are beginning to refer injured workers to the center.

"This work represents a significant breakthrough in the understanding and treatment of electrical injury," says Ron Wyzga, program manager for health studies in EPRI's Environment Division. "In addition, the prospect of being able to repair cell membrane damage has the potential for much wider application—as a treatment for other types of burns and for radiation injury, and even perhaps as an adjunct treatment during cancer therapy."

Two kinds of injury

Although the physiological effects of electric shock have been studied almost as long as electricity itself, the basic mechanism of electrical injury to cells remained unclear until very recently. At first, it all just seemed rather curious. In the late eighteenth century, for example, a court "electrician" amused Louis XV by using an electric shock to make 700 monks leap into the air simultaneously. The first documented fatality from an industrial electrical accident occurred in 1879, the same year that Edison invented the incandescent lamp. Although the unexpected pattern of progressive damage in apparently healthy tissue after electrical injury has been documented for more than a century, it has generally been attributed to heat generated by the passage of current.

In 1987, however, Dr. Lee, a plastic surgeon who also has a doctorate in electrical engineering from the Massachusetts Institute of Technology, began publishing a series of papers that demonstrated the traumatic importance of electroporation—cell membrane breakdown caused by strong electrical forces that occur in tissues during shock. While under most circumstances thermal damage requires electrical contact for seconds, electroporation can happen within fractions of a millisecond.

The thermal part of an electrical injury is usually readily apparent and ranges from mildly reddened areas to charred tissue at the site of a high-voltage contact. Often the sustained contact that causes extensive thermal injury results from the "no let go" phenomenon, in which the passage

Breakthrough in Electrical Burn Treatment

of alternating current causes flexor muscles in the hand to contract and prevents victims from voluntarily releasing their grip on an electrified object. Research on this kind of injury is expected to contribute to the design of electric safety devices that would sense a ground fault and open a circuit in time to minimize heat damage from an electrical accident.

Damage to tissues caused by electroporation, however, occurs almost instantaneously and may not show up for several days, as cells struggle to close membrane openings caused by fields and to reestablish internal equilibrium. Cell membranes are susceptible to strong electric fields because, unlike most other parts of the cell, they are held together by weak electrical forces rather than chemical bonds. If a ruptured membrane cannot be repaired in time, vital contents are lost from a cell until it dies.

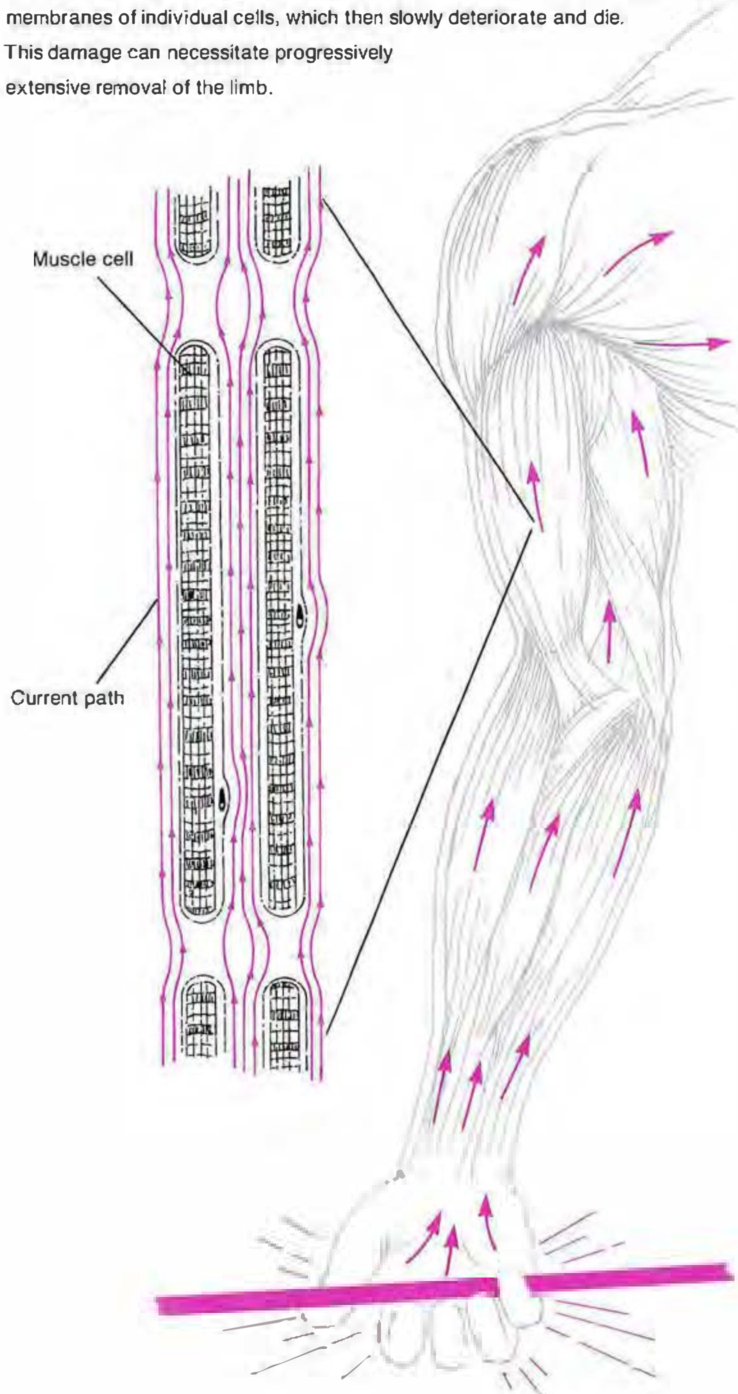
Search for hidden damage

Given the dual nature of electrical injury, the first step toward improved treatment has been to develop methods for detecting the initially hidden damage caused by electroporation and for monitoring the cell membrane repair process.

According to the currently accepted model, the basic structure of membranes is a double layer of phospholipid molecules. Each of these molecules has a hydrophilic (water-attracting) "head" and a hydrophobic (water-repelling) "tail." The phospholipids are arranged with their hydrophilic heads extending outward toward the watery intra- and extracellular medium, while their tails fill the narrow interior space between the two layers. The phospholipid molecules have considerable latitude for movement within the membrane bilayer; their movement is responsible for the appearance of transient pores in normal tissue.

Generating an electric field across a cell membrane causes pores, or holes, to appear. If the electric field is weak, the pores are temporary and lipid molecules quickly mobilize to close them, with help from specific proteins that also have alternating hydrophilic and hydrophobic segments. If the field is strong enough, however, the

THE DUAL NATURE OF ELECTRICAL INJURY An important recent discovery is that electrical burns typically result in two very different types of injury. Immediately recognizable is the thermal injury that results from the destruction of tissues at the point of contact. But the current from a shock actually passes through much of the body as it travels to ground, setting up strong electric fields along its path. These fields cause hidden damage to the membranes of individual cells, which then slowly deteriorate and die. This damage can necessitate progressively extensive removal of the limb.



pores become permanent, interrupting important cell processes and eventually destroying the cell.

One of the most important functions of a cell membrane is to control the movement of material into and out of the cell. In particular, protein molecules that extend through the phospholipid bilayer regulate the passage of ions, such as calcium, sodium, and potassium. This often involves "pumping" ions out of a cell into a more concentrated solution, a process that requires the expenditure of energy. If a significant number of pores appear in a membrane, external ions can move freely into the cell, leading to a serious electrolytic imbalance and causing the cell to swell with water, further enlarging the pores. At the same time, the cell begins to exhaust its supply of adenosine triphosphate (ATP) molecules, which provide the energy needed to restore ion balance and conduct membrane repair.

A variety of imaging technologies are now available to detect such metabolic changes and thus locate tissue damaged by electroporation. Magnetic resonance imaging (MRI), for example, uses electromagnetic fields to probe molecular changes, such as the dissociation of ATP during cell repair and the increase in concentration of various ions. By quantifying and imaging these changes in tissue exposed to electric shock, MRI can help a physician assess the extent and severity of damage that might not otherwise be apparent. MRI can also be used to detect edema (the accumulation of fluid in tissues) and to monitor blood flow through an injured area.

Although MRI images have exceptional spatial resolution, the equipment involved is not portable, and it is difficult to transport severely injured patients for frequent MRI examinations. Work is therefore under way at the University of Chicago's Franklin McLean Memorial Research Institute to develop smaller imaging devices that could be used for routine bedside examination. One promising candidate being investigated under EPRI contract is single photoelectron emission computed tomography (SPECT). In this technology, a patient is injected with very small amounts of radioactive isotopes that tend to concentrate in regions of particular metabolic activity. A technetium compound known as ^{99m}Tc-pyrophosphate, for example, forms a complex with calcium ions and thus can serve as a SPECT indicator of increased local calcium concentration following cell membrane rupture. Another ^{99m}Tc compound similarly indicates increased potassium ion concentrations. The rubidium isotope ^{86}Rb can be used to evaluate blood flow to electrically traumatized tissue.

Other new diagnostic techniques are also being developed. One critical indicator of the severity of electrical injury is its effect on the electrical impedance, or resistivity, of tissue. Researchers at the University of Wisconsin have found, for example, that a decrease in impedance of more than 50% is always associated with death of muscle tissue, while a decrease of less than 40% generally indicates survival. In the case of nerve tissue, the extent of damage can be estimated by measuring the ability of nerve bundles to distinguish between two mild shocks separated by a brief period of time, the so-called refractory period test.

Sealing injured membranes

The second step toward improving the treatment of electrical trauma has been the search for a drug therapy that can initiate the sealing of electroporated cell membranes. Taking a hint from the natural healing process, in which proteins help close spontaneously occurring membrane pores, the University of Chicago team began examining the effects of various materials with alternating hydrophilic and hydrophobic segments, which might bind to the edges of pores in a membrane and initiate sealing.

Surface-active copolymers, or surfactants, looked particularly promising. This broad class of materials includes numerous detergents, emulsifiers, and wetting agents, whose properties can be tailored to specific applications by changing their chemical structure. In particular, Poloxamers—copolymers consisting of hydrophobic propylene segments and hydrophilic ethylene segments—have proved safe and useful in several previous medical applications.

Initial experiments with surfactants involved exposing isolated muscle cells to electric shock and watching their response to various treatments. The extent of electroporation was measured by observing the release of fluorescent dye from each cell. For cells in a neutral saline solution (controls) the loss of dye was both dramatic and continuous; for cells bathed in a Poloxamer, dye release was markedly slower and nearly stopped after only 4 minutes. The implication was that surfactants could, indeed, help seal cell membranes—at least *in vitro*.

The next critical experiment was to measure the effects of Poloxamers in living tissue—the biceps muscle of rats, which were deeply anesthetized for the procedure. In these tests, when a flap of muscle was shocked, its electrical impedance quickly fell to about 50% of normal—the level usually associated with permanent tissue damage. Intravenous treatment with a Poloxamer 20 minutes after the shock, however, was able to bring the impedance level back to about 80%, where it remained stable—indicating likely membrane repair. Surprisingly, when the Poloxamer was administered to a rat *before* the muscle was shocked, impedance stabilized at about 96% of normal. After 24 hours, the muscle tissue of both groups of rats treated with the Poloxamer showed none of the progressive damage that would have been expected from electrical trauma—a finding that suggests possible long-term recovery of function. This is the first time that damage to cellular membranes has been repaired through therapeutic intervention.

Additional evidence of the effectiveness of Poloxamers was provided by electron microscope photographs of cell membranes that had been pretreated with a Poloxamer. These micrographs showed evidence of interactions between the electrically induced pores and the surfactant: The membranes appeared to be undergoing a repair process.

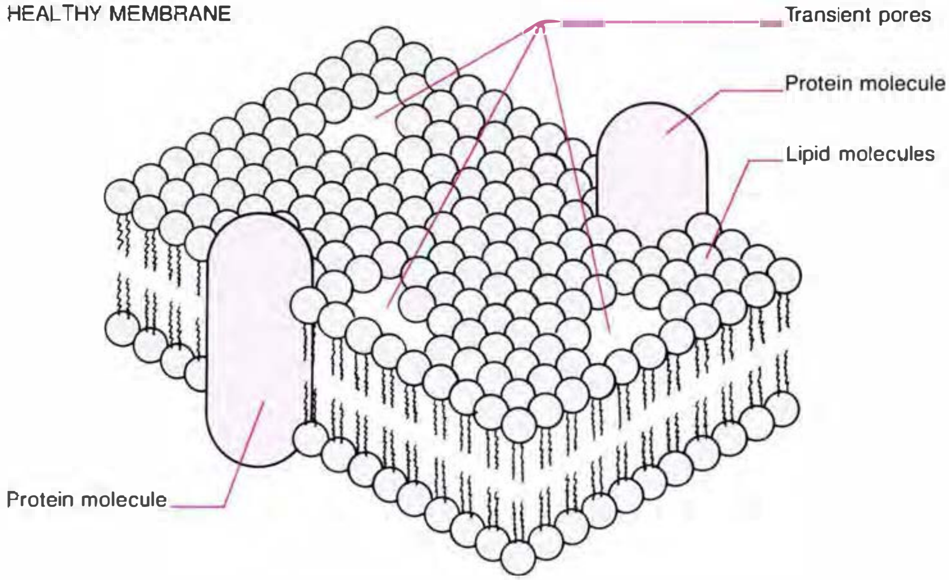
On to clinical trials

Such promising results have encouraged

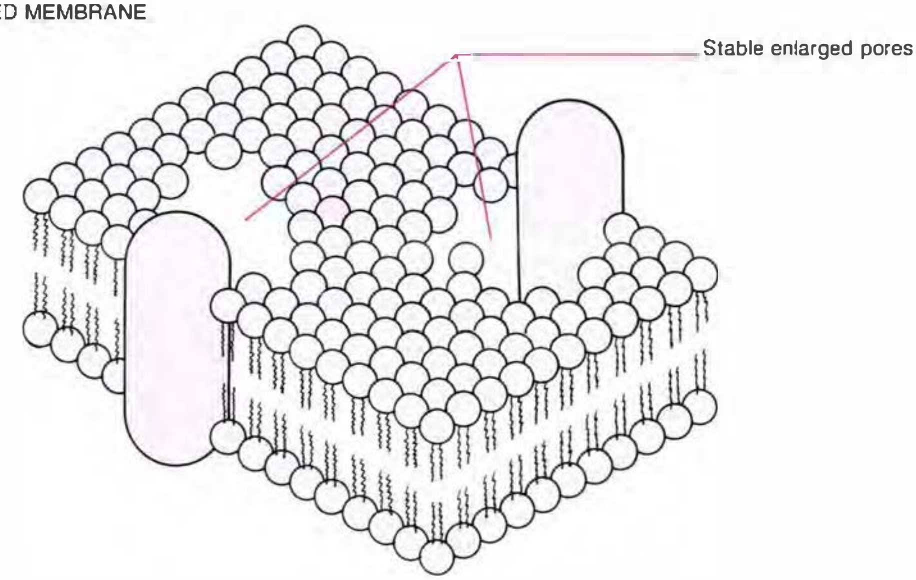
TREATING INJURED MEMBRANES

A cell membrane is a complex structure consisting of a double layer of lipid molecules that is penetrated by larger protein molecules. The protein molecules regulate the passage of ions in and out of a cell. When electric fields create large pores in a membrane, ions can flow freely, destroying the internal balance and leading to cell death. EPRI-sponsored research has demonstrated that intravenous injection of surface-active copolymers can be used to seal pores until natural repair processes can take over.

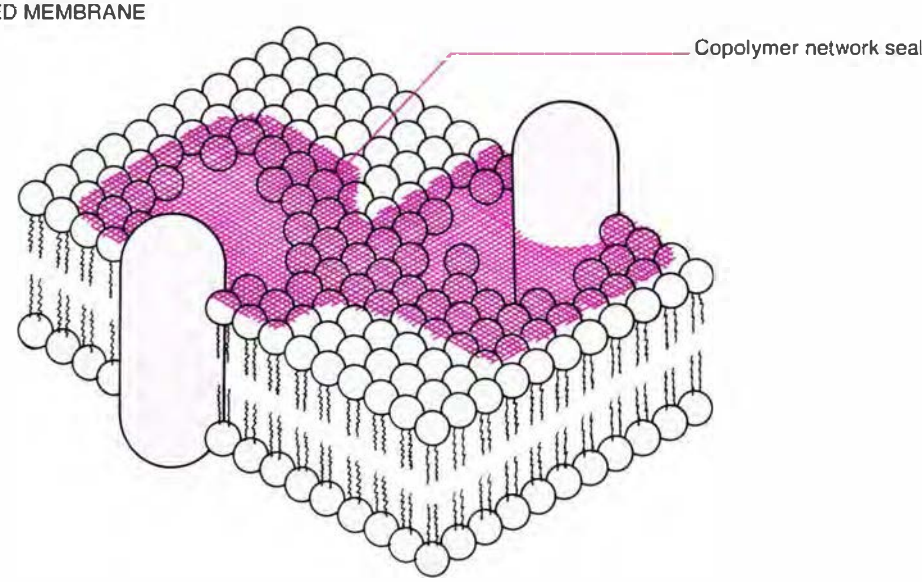
HEALTHY MEMBRANE



INJURED MEMBRANE



TREATED MEMBRANE



A VIEW OF HIDDEN DAMAGE Membrane damage caused by electric fields may not be apparent in affected cells, even when they are evaluated during surgical intervention. Such cells nevertheless undergo changes that can be detected with the aid of radioactive isotopes that concentrate in regions of particular metabolic activity. This view of an injured patient, made with the use of single photoelectron emission computed tomography (SPECT), clearly delineates the burned area of the torso but also shows underlying damage in otherwise healthy-looking areas of the shoulder and neck.

researchers to move quickly toward the use of Poloxamers to treat patients at the Electrical Trauma Center. "We hope to move to clinical trials in 1993," says Dr. Lee. "We could start tomorrow if we had the bedside diagnostic equipment, but it has to be custom-built, and we need it to monitor recovery."

Specifically, the University of Chicago team is formulating a therapeutic strategy involving the administration of Poloxamers and a solution containing ATP, which could have a priming effect on the ability of injured cells to synthesize ATP on their own. Diagnostic tests will enable the researchers to determine the effects of different mixtures of Poloxamers and control other variables in order to optimize the healing process.

If this new therapy is successful, it may be applied to the treatment of other injuries in which membrane damage is a major component. These include some low-temperature, nonelectrical burns, such as scalds, and injury caused by exposure to ionizing radiation. "There's no existing treatment for radiation damage," says Dr. Lee, "and we're interested in pursuing the use of Poloxamers for this application. If they prove effective, it will be a major accomplishment."

More speculatively, surfactants might conceivably be used to protect the membranes of healthy cells around a tumor during radiation therapy for cancer. This therapy is based on the principle that tumor cells, which are rapidly dividing, are more susceptible than normal cells to damage from free radicals (chemically active molecule fragments) created by the passage of ionizing radiation. The potential problem is that surfactants might also act as scavengers for the free radicals, thus protecting cancer cells as well as normal cells. The fact that a variety of other diseases, including muscular dystrophy and several neurological disorders, also involve cell membrane damage raises the possibility that surfactants could at least provide a new research tool for their investigation.

"I believe that the use of Poloxamers will eventually become routine for treating electrical burns and possibly a variety of other problems," says Dr. Mary Capelli-Schellpfeffer, medical director of Wisconsin Electric Power Company, which is one of the cofunders of the University of Chicago work. "This project has offered our utility an opportunity to focus research effort on an area that could directly affect our employees if they are burned. Most electrical burns do not involve utility personnel, however, so this effort also shows our commitment to help members of our community who might need this treatment.

"In addition, the Electrical Trauma Center provides a unique chance to enhance our understanding of electrical injuries and to bring together in one place a sufficient number of patients to get dependable findings about new treatment technologies. We're only 40 minutes from Chicago by helicopter, but patients could be brought from as far away as the West Coast within the critical time for starting treatment. The center is a resource for the industry, and we should support it so that promising technologies can be developed quickly and made available elsewhere."

Even before clinical trials using Poloxamer therapy begin, the Electrical Trauma Center is accepting patients who need specialized medical and surgical treatment for major electrical injuries. Dr. Lee expects the eight available patient rooms to be readily filled, and he says that the average patient stay will probably be six to eight weeks. In addition, the diagnostic techniques already developed have provided important insights into some past injuries. One woman from Louisiana, for example, was examined at the center and found to have residual nerve damage from an electrical accident three years ago. This discovery helped her obtain better treatment back in her home state.

"There are between 1000 and 1500 severe electrical burn cases a year in the United States that require the kind of specialized treatment now available at the Electrical Trauma Center," concludes Ron Wyzga. "I anticipate that similar centers will eventually be established in other regions of the country; they will undoubtedly use some of the diagnostic techniques and surfactant therapies now being pioneered at the University of Chicago. EPRI will continue its commitment to this research, which will be of great direct benefit not only to utilities and their workers but also to the general public." ■

Background information for this article was provided by Ron Wyzga, Environment Division.

ELECTRICAL INJURY PROJECT SPONSORS

Electric Power Research Institute
Empire State Electric Energy Research Corporation
Niagara Mohawk Power Corporation
Northeast Utilities
Public Service Company of Oklahoma
Public Service Electric & Gas Company (New Jersey)
Wisconsin Electric Power Company


PREPARING

FOR DISASTER

by Bob McGee

THE STORY IN BRIEF *Hurricanes Andrew and Iniki, two of the most devastating natural disasters in the nation's history, have focused the public's attention on the frightening power and unpredictability of the forces of nature. While full recovery in Florida and Hawaii will involve infrastructure repairs far beyond power restoration, the destruction wreaked by these storms underscores the importance of emergency planning for utilities as well as government groups. Case studies from past disasters—now well understood and documented—and the results of an EPRI-hosted conference on disaster preparedness outline key elements for an effective utility emergency response plan. Recommended are the preparation and maintenance of emergency headquarters with independent communication lines; in-place agreements with other utilities, public aid groups, and government bodies; and a positive ongoing relationship with the news media—a utility's main connection to the outside world during a disaster.*

WITHIN 30 DAYS IN THE FALL OF 1989, TWO MAJOR DISASTERS OCCURRED that threw large regions of the country into chaos. On September 20 and 21, Hurricane Hugo smashed into the East Coast with a ferocity that wreaked havoc, passing Charleston, South Carolina, with 140-mph winds, then winding its way up to Charlotte, North Carolina, which it hit with gusts of up to 100 mph. A few weeks later, on October 17, the Loma Prieta earthquake, measured at 7.1 on the Richter scale, shook up northern California. It lasted only 15 seconds, but it devastated pockets of homes and businesses from San Francisco to Santa Cruz, collapsed a section of double-deck freeway in Oakland, and felled a piece of the upper roadway of the Bay Bridge, which connects San Francisco and Oakland.

Causing billions of dollars in damage and leaving bewildered residents without power, both events put utilities' emergency plans to the test. Looking into the progression and outcomes of these incidents has given representatives of utilities, regulatory agencies, and research groups an opportunity to study how to most effectively plan for disasters. Most of the country should be interested. Given earthquakes, floods, hurricanes, snow and ice storms, and tornadoes, few areas are not at risk. Utility systems can even be damaged by geomagnetically induced currents triggered by unusually heavy sunspot activity.

"Emergency planning is not something that pushes itself in your face under normal circumstances," says EPRI project manager Ben Damsky. "As practices change, new equipment is installed. As the system grows, you need to take a closer, more thorough look at your plans. If you neglect emergency planning, you don't get any feedback until the problem hits you, and then it's too late."

A little over a year after the nation suffered the devastating Hugo–Loma Prieta double whammy, EPRI hosted a conference in the San Francisco Bay Area that was attended by 60 U.S. and Japanese representatives. While the type and severity of disaster incidents may vary, conferees agreed on several points that are important for any utility's preparedness planning; these are outlined in *Proceedings: Wide-Area Disaster Preparedness Conference* (EL-7298).

The first, and most obvious, point is that it is essential to have an overall plan that is known throughout the utility and that is regularly rehearsed and updated. A plan that exists only on paper is not much more effective than good intentions. To ensure effective coordination of efforts, facilities must be prepared for use as emergency headquarters, complete with redundant communications and access to system drawings and data. During an emergency, the interim use of power lines may be nonstandard, and knowing how and where to temporarily adjust relays can make a crucial difference in bringing customers back on-line. A stock of replacement parts should be stored, and arrangements should be made with neighboring utilities to share hardware and heavy equipment. Here again, communications are key to the execution of an orderly plan and should include connections with local, state, and federal government agencies, including the military. Finally, the conferees agreed, media relations are very important in disaster planning. It's tempting for utility crews to see restoration of power as the end point of concern, but the public's perception—largely influenced by news media coverage—is the real measure of success for a disaster recovery operation.

God and the people at the power switch

Acts of God become a big liability for company reputations when actions of utility management fail to mitigate damage in what the public feels is a reasonable period of time. "God is becoming less of a factor," says EPRI technical advisor Robert Iveson, "and utility management is becoming more of a factor, at least in the public's mind. When more than one utility is involved and one performs well and the other doesn't, you've had it." In one instance, an unexpected early fall snowstorm blacked out the service areas of several utilities. One utility took two days longer to get back on-line than the neighboring utilities, and neither its customers nor its regulators were happy. When the regulators looked, they found the emergency plans deficient.

One of the best-prepared companies for snow, ice, and storms is Central Maine Power (CMP), which covers a service area subject to both extreme coastal and extreme inland storm patterns. "We have a bill insert that we use twice a year—in summer and winter—to make sure people are prepared for an outage," says Tim Vrabel, supervisor of community relations. "We make sure our line crews have a lot of depth when we know a storm is on the way; aside from our regular backup crew, we might have one or two other crews. If it's going to be a heavy snow, we'll have our chains on the night before."

CMP also has a complete manual for emergency power restoration and a network of mutual aid that involves hundreds of people from other utilities in Canada, New Hampshire, Vermont, and Massachusetts, plus a private contractor that helps with transmission work.

One of the planning characteristics that helps improve response, according to Iveson, is institutionalizing accountability within the utility. Naturally, backup plans are key. Not only do you need backup emergency control and emergency operations centers at a site away from the primary centers, but you also need contingency plans for whatever might have to be replaced. This is one of the reasons emergency planning needs to be extensive, and one of the reasons the plans need to be reviewed regularly.

Typically, much of the consideration given emergency planning by utility management revolves around economics. A region's economic welfare has an impact on

Herman Kokojan/Black Star

Marvin Silver

Marvin Silver

Marvin Silver

WORKING ON THE PROBLEM The emergency operations center is the heart of restoration efforts, coordinating a broad range of round-the-clock logistical demands, including worker dispatch, requests for equipment and assistance, feeding of crews, and news media information updates.

Lewis Stewart/PG&E

Joyce True/PG&E

Lewis Stewart/PG&E

the level of emergency preparedness the local utility is willing and able to maintain. When a region is experiencing economic difficulties, there is a potential for decrease in emergency preparedness. How a utility spends money is not just its own business, either. A company may have to convince its public utility commission that an expenditure is prudent in the context of all its options. Top preparedness at any cost may not be seen as an option when local economic distress clouds the issue.

Iveson feels that every company should have an emergency preparedness plan geared to those phenomena most likely to threaten a company's system. He also believes that the plan should encompass training activities and dialogue with other agencies. In what he calls a balanced viewpoint, Iveson believes an emergency plan should be tailored to the financial situation of a utility. "Managements tend to take each company's emergency plan on a case-by-case basis and to prepare most rigorously for the problems they are most familiar with," says Iveson. "A utility that has recently had a bad experience, with all the attendant publicity and regulatory scrutiny, will spend a lot of time on emergency planning. Others will not. There's a sensitivity to the business risk in making a choice that reduces your ability to respond. In the end, the level of preparedness becomes a business decision."

Sam Mullen, a planning coordinator who has spent 24 years with Atlantic Electric and who has spent the last 6 years working on emergency planning, feels the issue should have a higher priority at all utilities. "In between disasters, utilities can develop a sense of complacency and overconfidence. Utilities generally need to develop plans in greater detail, and they need to regularly revise them," says Mullen, who wrote his own company's storm plan. "You should have not only an annual test but periodic tests of various entities. For instance in the T&D area, I hold damage survey exercises. I send out personnel to survey feeders and different types of equipment and write up statements about damage. It gives them the opportunity to learn more about the system."

On the Scene in San Francisco

One of the ultimate earthquake survival experiences perhaps was that of PG&E gas construction foreman Kevin Scannell: "I was in a hole cutting service off when I looked up at the two guys standing above me. Their faces had gone white, and the building behind them was swaying. I was at eye level with the street, and I saw a 3-foot-high wave of concrete rolling down the street toward me."

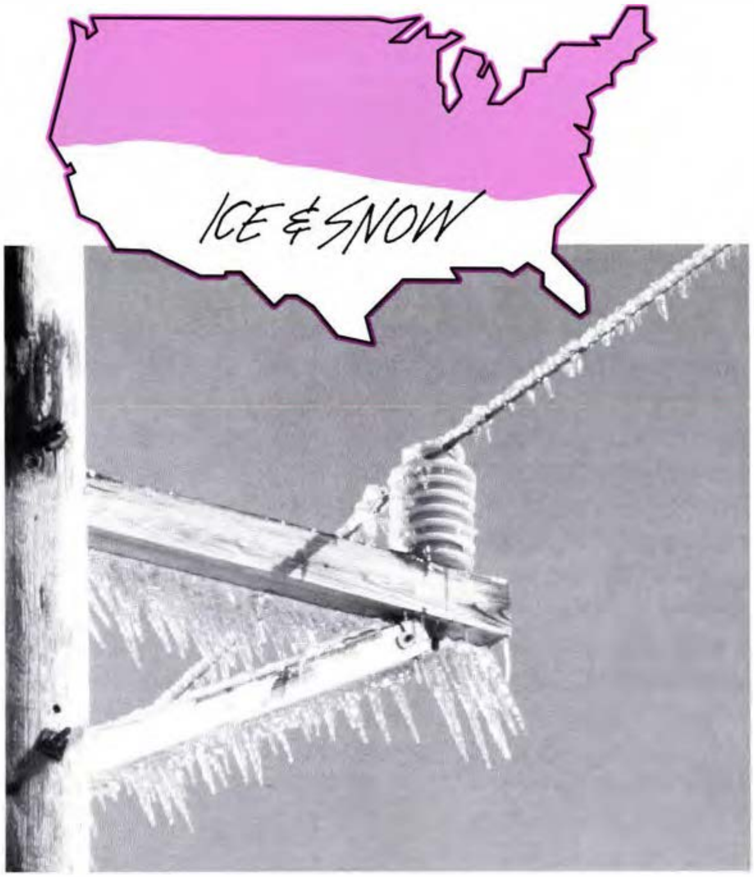
When the 15 seconds of shaking finally stopped in San Francisco's Marina District on October 17, 1989, no one on Northpoint Street near Fillmore was prepared for what they saw: cracked facades, the front of an automobile suspended in midair after a street had risen up under the middle of it, and finally, down on the corner, a three-story building that had collapsed into itself.

Power was out, and a plume of smoke could be seen rising from a few blocks away, at Beach and Divisadero, where a fire raged out of control. Emergency relief efforts were already being coordinated at the Marina Middle School under the auspices of the mayor's office. Many people, out of their homes, would sleep elsewhere and wait for an official inspection before going back in.

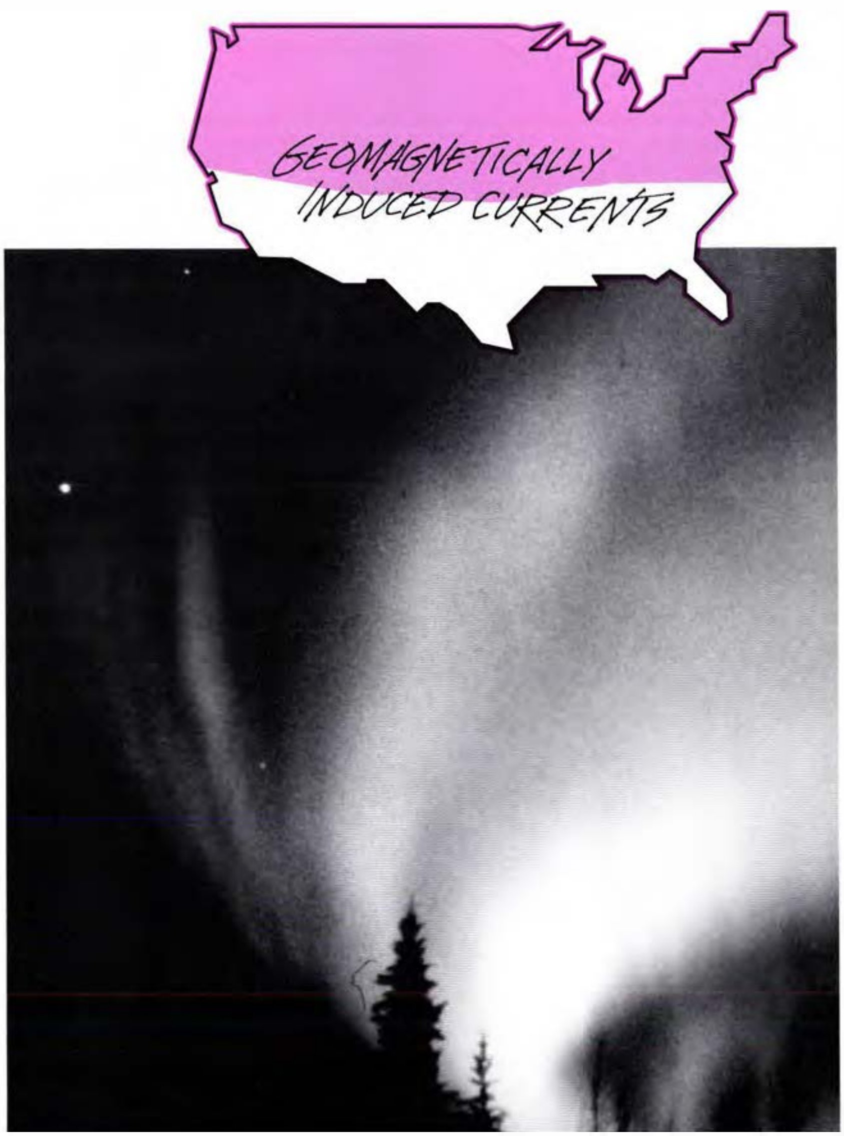
Given the fire in progress, and reports of the smell of gas coming from all over the Marina, gas distribution engineer Brian Leary made a decision: "I said the Marina District gas system had to be shut down immediately. People looked at me like I was crazy, because we had never shut down a low-pressure system before for any reason. But I shouted everyone down." Electricity service was restored within days. Gas was another matter. Damage was so severe that the entire gas system had to be replaced. Handling this effort made PG&E some friends.

For several days, PG&E was working in the street until late in the evening. In the weeks that followed, drilling would begin at seven in the morning and end at seven at night; the area would be cleaned up as much as possible when work was done each night. Residents were kept informed of the progress and were told that Thanksgiving—over a month away—was the target date by which everyone could expect gas service to be restored. With service personnel from other utilities throughout the West joining in to assist in the restoration effort, PG&E would beat its own schedule.

To help residents cope while they were without gas service, the utility brought in trailers with showers, often used for firefighters battling forest fires. The repair efforts and clear concern for their customers earned the company a spontaneous outpouring of affection from the local residents. The homemade signs many put up in their windows when the work was done said it simply and gratefully: "Thank you, PG&E." □



Otter Tail Power Co.



University of Alaska

Mullen has outlined 35 specific tasks in Atlantic Electric's operation that he believes are essential. He has also outlined 35 different emergency response fields in his company's computerized personnel system. The system is coded, providing people's capabilities on REDI (responder's emergency duty instructions) sheets. "All of us who hold jobs in non-customer-contact areas in this 2000-employee company," says Mullen, "also can assess damage, do other operational and support jobs, or help with customer contact functions in an emergency."

The priority given to emergency planning is important to Mullen: "Every company has its top 10 issues. Emergency planning may slip down the list from time to time. Even though people may believe in it, it may never get top billing. I'm not comfortable with that—emergency preparedness and planning is essential to lives and livelihoods. It's just that important."

Reality checks

Hurricane Hugo hit Charleston on September 21, 1989, just after midnight. It then moved northwesterly through the South Carolina Electric & Gas service area, passed through a section of Carolina Power & Light's territory, and finally curved north and split Duke Power's territory. Fully 300,000 of 470,000 SCE&G customers were affected; so were 140,000 of CP&L's 900,000 customers and almost 700,000 of Duke Power's 1.6 million customers. Together, the three companies had 600 transmission structures and 16,000 poles damaged and had to replace 27,608 distribution transformers. Duke Power alone had 9000 craft and professional workers involved in the restoration process, and this force was supplemented by 2600 workers from other companies; people came from 11 utilities in 16 different states to help.

When Duke Power activated its Distribution Emergency Center, bracing for its first-ever experience with a hurricane, the utility was using its Emergency Workforce Management System, a mainframe computer program, to track and sort resource requests and record personnel movements. "Statistics such as poles down, customer outages, weather information, personnel at specific locations, personnel in transit, departure times, and estimated arrival times assisted greatly in the strategic management of resources," said Richard M. Johnston, a company distribution operations systems supervisor, in a 1990 report to the Southeastern Electric Exchange.

With 98% of Duke's Charlotte customers affected by outages, customer calls were recorded through the utility's Emergency Service Restoration System. This system was used to identify locations where field assignments should be made to expedite service restoration. And once restoration had progressed significantly, the system provided a customer callback tool.

During the emergency, Duke's Transmission and Design Engineering Department provided personnel to act as guides, scouts, and damage assessors. Right-of-way clearance personnel were assisted by laborers from different departments. Heavy equipment operators from Duke's Construction Maintenance Department helped move debris, allowing truck access to damaged facilities. Logistical assistance emerged as one of the most critical functions, from organizing lodging plans to preparing meals for emergency workers. Substations, schools, shopping centers, and hotels were used as satellite command centers, according to Johnston, reducing congestion and making it possible to maintain more effective and efficient management.

"Since Hugo, a total review of all emergency plans has taken place," says Johnston. "Our previous plans worked, but they have been expanded and improved to better address catastrophic events such as hurricanes. Further definition of the special abilities of other departments has been added. Areas for additional training have been identified, and that training has taken place for many groups."

Johnston adds, "One point to emphasize in any plan is the preassignment of personnel to specific responsibilities. When personnel are aware of what they will be responsible for, they are more ef-

Practice Makes Perfect at LILCO

Suburban Nassau County and the suburban and rural reaches of Suffolk County on New York's Long Island have a weather history that includes more than a brush with dangerous storm patterns: they've been hit by hurricanes. Long Island Lighting Company (LILCO) knows how to prepare for them.

LILCO's emergency restoration preparedness efforts were significantly enhanced in 1985–1986, after Hurricane Gloria blew through the service area in a direct hit and knocked out power to 800,000 of the utility's 1 million customers. It took 11 days before power was restored to everyone. Then, last year, Hurricane Bob interrupted service for 477,000 customers; full restoration took four and a half days.

LILCO's Electric Service Department has established personnel assignments and comprehensive procedures for use during major restoration efforts. These procedures address all aspects of emergency operations, including storm anticipation, mobilization of personnel, mutual assistance crew support, command and control, localized restoration, system survey, delivery of materials, communications, and data reporting.

To keep its people ready to put these plans into action, LILCO conducts a series of emergency drills that cover field, divisional, and headquarters operations. All of LILCO's 6500 employees participate, and every employee has a special, nonstandard duty to perform in an emergency. "Our efforts include classroom as well as field training," says Werner Schweiger of LILCO's Electric Service Department.

Each year employees assigned to substations undergo refresher training at LILCO's Hauppauge facility. Then, in January and February, operators working in pairs pick up IBM 55-SX workstations preloaded with a disaster simulation, set them up at assigned substations, log on, and go through the emergency scenario. Fictional damages are reported, giving personnel the opportunity to file simulated repair orders; progress in effecting those repairs is followed at both divisional and corporate headquarters.

In addition to entering damage repair orders, substation personnel enter manpower information and restoration estimates and provide rapid survey information that serves as an early indicator of storm damage; they also provide information on access to critical facilities and lodging capacity for mutual assistance crews. The drills last 8 hours and encompass 25 substations each day over the course of four days. In May and June, the drills are repeated in anticipation of hurricane season.

These emergency drills complement a full field drill conducted in April, which further tests workers' skills in the actual work environment. This drill involves patrolling and surveying the distribution circuits around 105 substations throughout the system. On each of five days, one-fifth of LILCO's service territory is covered; the personnel involved are totally devoted to the drills during that time, with their regular duties covered by personnel in other parts of the company. Any substandard conditions, or necessary follow-up procedures such as tree trimming, are reported and subsequently handled.

"The company has the commitment to support the effort," says Schweiger, "and our experience shows just how important that is." □

fective. Another point is more frequent drills. We conduct yearly drills in which our field personnel use the computer programs to simulate an emergency. Practice is required for efficient performance during any emergency."

Mutual assistance was also a concern in revising the emergency plans. "A checklist was developed for review with all visiting crews in order to clarify operating procedures and policies," Johnston says. "If we face another long-term restoration process, we plan to rotate off system workers after five to seven days. Extended periods of abnormal working hours, coupled with being away from family, compound fatigue and take a definite toll on morale and productivity."

Duke's revised plans also call for building a stronger relationship with both the State Emergency Management Agency and the military. And a safety review and examination of work methods, which are always a concern when the various contracts, safety rules, and work practices of different utilities and contractors overlap, yielded an interesting decision: "In most situations, visiting crews will follow their normal safety rules and work practices rather than ours." The idea, after all, is to safely and swiftly accomplish service restoration. The introduction of new safety rules and work practices reduces productivity and adds to management complexity.

Other important observations of Johnston's report included the effectiveness of Duke Power's nightly strategic planning sessions for the big-picture view, which enhanced the likelihood of sound reassignments the next day, and the importance of daily status reports in keeping morale and motivation high. A day-care facility created during the emergency period has been refined and added to the emergency plans. Provisions for employee family support and a toll-free phone number for family emergencies have been added as well.

Also mentioned were Distribution Emergency Center expansion and computer program enhancements. The answering of calls by Duke executives and programmers during the emergency was deemed valuable, especially since it gave them a first-hand sense of customer response to restoration efforts and a better insight into potential programming enhancements.

Putting the drills to work

Pacific Gas and Electric serves 4.1 million electricity customers and 3.4 million gas customers in a service territory covering 94,000 square miles in northern and central California. Centered 8 miles northeast of Santa Cruz, the Loma Prieta quake interrupted electricity service to about 1.4 million customers; the company's own general office complex and Energy Control Center in San Francisco were affected. As PG&E president George Maneatis said, "The lights went out and I knew we'd lost San Francisco. I called downstairs to power control. We were in very serious circumstances. The earthquake was the worst crisis in my 36 years here."

According to PG&E supervising power system engineer Ted Reece, damage was sustained at the Moss Landing power plant, the Metcalf substation, and the San Mateo substation, which in turn tripped other plants, ultimately affecting Monterey, Santa Cruz, and San Francisco.

The first service was restored in about an hour, and over 98% of the blacked-out customers—all but 26,000—had their power back within two days. Yet in San Francisco that dusk, only the lights of the Bay Bridge and a stretch of Market Street

A. T. Willett/Image Bank

were lit as people assessed damage and waited for the quake's aftershocks. In a couple of areas, such as the city's Marina District, gas main replacement was required. With crews regularly working 12-hour days seven days a week, that process was completed in four weeks.

As Reece reported to the Wide-Area Disaster Preparedness Conference, the primary responsibilities of PG&E's Energy Control Center (ECC) are dispatching generation resources and monitoring and coordinating the operation of the 500- and 230-kV transmission network. "Unlike control centers at many utilities, the transmission network is not controlled directly by a supervisory control and data acquisition (SCADA) system. That responsibility is delegated to regional switching centers and power plants. A real-time dispatch computer is used to monitor the system and control the generation," he noted. "In addition, ECC personnel coordinate PG&E's operation with other utilities throughout western North America."

Unfortunately, a new energy management computer system was being installed at the time of the earthquake, and some of the emergency power supply facilities were not in operation. "The dispatch computer performing the automatic generation control functions failed at the time of the earthquake, when shaking caused the disk drive to malfunction," reported Reece. "We were actually in the middle of a systems transition at that time, and since the new installation, all the disk drives have been given their own seismic bracing. However, most of the problems in the ECC were caused by the loss of our own power and the failure of backup power systems."

A by-product of the confusion and the lack of power, Reece noted, was the "inadequate space for support personnel and quiet places for dispatch personnel to gather their thoughts." Power flow analysis was also initially difficult without computers. Many of the critical ECC functions remained out of service until 6:30 p.m., almost an hour and a half after the quake. However, PG&E telephone, microwave, and radio systems all remained intact during the quake and were vital to obtaining resources and coordinating operations.

"The value of PG&E's private communications network was clearly demonstrated in the aftermath of the quake," says Augie Nevolo, chief telecommunications engineer at PG&E. "While the public telephone network quickly jammed up with an overload of calls, our telephone system was able to handle emergency response calls throughout our service territory. In fact, our network was used by state emergency response agencies needing to call San Francisco."

As a result of Loma Prieta, PG&E has enhanced its backup ECC and, according to director of corporate security Lyman Shaffer, has tested alternative headquarters, expanded cellular capabilities, established emergency operations centers at its regional organizations, and put a database management system on-line. "The model we've developed," he adds, "has been mirrored by the southern California utilities."

A PG&E earthquake drill, in advance of Loma Prieta, was one of the most important testaments to the company's preparation. It ultimately made PG&E employees and their mutual aid partners heroes for their customers (see sidebar). "You have to have a plan and test the plan," says Reece, who agrees that the emergency preparedness exercises are key. "I think we're learning each time. The desire for information is driving the drills. Lines of communication and responsibility need to be clear and not interfere with the restoration

PARTNERS IN YOUR PLAN

Connections with other organizations can be crucial to the efficiency and effectiveness of disaster response efforts. Setting up relationships ahead of time and maintaining them as part of the emergency response plan will ensure good coordination when help is needed.

Restarting When It's Black

What do you do if there's a major disaster and your power system collapses? "Blackouts present very unusual problems for a system operator," says EPRI project manager Gerry Cauley. "Under normal conditions, the system is constantly kept on an even keel through switching adjustments and gradual shifts in generation and load. After a blackout, it can be very difficult to determine how the system will behave: you've got to build the system back up piece by piece in an order that ensures the safety of personnel and equipment while restoring customer service as quickly as possible."

EPRI is now developing new software called the Expert Advisor for System Restoration to help operators get their service areas out of the dark more quickly. "Essentially, the software serves as an advisor to suggest a plan to get back on-line," says Cauley. "The program uses special simulation tools combined with rules based on expert knowledge. In the event of a major blackout, the program gathers information from the control center's energy management system computer and provides information to the operator about which units to start and the sequence in which to start them. It also gives operators sets of switching procedures to provide outside power to large generating units to get them restarted." In addition to helping the operator cope during an emergency, the advisor can be valuable as a restoration training and planning tool.

The software, which is now available as a knowledge-based prototype, was developed by Philadelphia Electric Company and, in its present form, is based on that utility's system. Still, the advisor is about 80% generic, and the rules can be modified to customize it to another company's system. EPRI currently has an active group of advisors from 10 utilities providing input on design, and it will soon select a second host utility system for a commercial-grade version of the program, which will also include the special simulation tools required to model system behavior during a restoration. This version is expected to be on the market by the first quarter of 1994.

At that time, the program will be fully integrated with the EPRI Operator Training Simulator for use in restoration planning and training. The final version for implementation in control centers is planned as a collaborative project for 1994–1995.

Cauley feels the expert advisor will go a long way toward giving every utility the capacity to reestablish its own system quickly after a total collapse. But he is quick to point out that the software does not provide for completely automatic restart: "If you are bringing the system up unit by unit and substation to substation, you still have to reenergize each of them. While the commercial software will be able to help in this operation—checking frequency to see if there's too much generation-load mismatch or if voltages are too high, for example—it's still the operator's show.

"We're putting information in the system that's based on prior knowledge, and it's the operator who may know there's something wrong with a particular unit or line. The computer will never provide the total answer—that's why the operator will always have an essential role in restoration. There are too many uncertainties and too many things that can go wrong. The operator is still the person in charge." □

Rob Nelson/Black Star

effort. There are ways of getting information that don't interfere with or impede operations."

Sharing parts and information

While the importance of human resources in responding to an emergency cannot be overstated, putting a power system back on-line will inevitably require spare parts to replace components damaged in the disaster—sometimes, as in the case of Hurricane Hugo, tens of thousands of pieces. To prepare for such needs, many utilities regularly exchange data on distribution parts and materials that can be made available to neighboring companies on short notice. It is not uncommon for utilities that have material inbound from a vendor for their normal inventory to redirect the order to a utility in an emergency and reschedule the original shipment for a later date.

Other organizations also provide assistance in this area. The Edison Electric Institute created and maintains the Mutual Assistance Plan, which compiles and updates lists of transmission and distribution equipment that its member utilities can make available to their neighbors in case of a calamity. The North American Electric Reliability Council, or NERC, keeps a comprehensive database listing the availability of major power transformers from virtually every utility in the country. This information can be particularly important because, unlike most distribution equipment, power transformers are nearly custom-made to the requirements of each generating station and are difficult to repair; finding a closely matched replacement unit quickly can save a utility many months of replacement power at a cost of hundreds of thousands of dollars a day.

Sharing people and parts may get the power back on, but as EPRI's Iveson stresses, sharing information with the customer may turn out to be the most important factor in a restoration operation: "When the power goes off in such an electrified society, the dominant feeling is one of helplessness. The utility not only has to work hard to restore power, it has to make it clear to the public that it knows what it's doing—that the *utility* is not helpless. This means that relationships with the media are crucial, especially at the start of a crisis, when information is at a premium."

Stacey Shaw, a manager of media relations at Florida Power & Light, agrees; she points out that the concept applies to the work of customer service representatives as well as to that of a media liaison: "A company's perception of customer needs tends to be restoration-oriented, and there's no question that restoring power is the top concern. But sometimes we forget that the customer perception of what is going on is also very important. Some companies that have extremely good restoration efforts don't get that message out fast enough to the customer. The best programs are very strong in sharing minute details." And, she adds, "the better your relations with the news media *before* the emergency, the more accurate they are likely to be in telling your story." ■

Background information for this story was provided by Ben Damsky, Robert Iveson, and Frank Young of the Electrical Systems Division.

TECH TRANSFER NEWS

EPRICON Restores ESP Performance

As many utilities shift to lower-sulfur coal in response to the 1990 Clean Air Act Amendments, they face a complication—the adverse effect such a shift can have on electrostatic precipitator (ESP) performance. Reducing the coal sulfur level from 3% to less than 1%, for example, can increase particulate emissions from an ESP by as much as a factor of 10. A recently patented EPRI invention—EPRICON—reduces the cost of restoring ESP performance after fuel switching and thus increases the practical options utilities have for complying with the amendments. About half the plants affected by the amendments are candidates for fuel switching, and virtually all of these units are equipped with ESPs.

ESP performance depends on the resistivity of fly ash, which in turn is controlled by sulfuric acid vapor in the flue stream. This vapor forms from SO_3 produced by the combustion process. A switch to lower-sulfur fuel reduces the amount of SO_3, thereby degrading the efficiency of the ESP. In the past utilities have compensated for this change by injecting SO_3 into the duct ahead of the precipitator, but conventional SO_3 conditioning systems are costly and require storage and maintenance of chemical reagents.

The reagentless EPRICON process operates by withdrawing 1–3% of the hot flue gas from the boiler and passing it through a catalyst that converts some of the SO_2 in the gas to SO_3. The SO_3-enriched stream is then injected back into the flue duct ahead of the ESP. Since it takes advantage of the existing pressure drop in the main flue gas system, EPRICON does not require a fan to move the SO_3-enriched sidestream. And because it derives the SO_3 from SO_2 already in the flue gas, the process does not add sulfur emissions to the air.

A catalyst test facility operated for over a year at Alabama Power Company's Plant Miller has produced encouraging SO_2-to-SO_3 conversion efficiency results, including indications of a relatively long catalyst lifetime. Preliminary estimates also indicate that EPRICON will be significantly less costly to install and operate than conventional SO_3 conditioning systems. EPRI is currently negotiating licenses with potential commercializers and is looking for a host site for a full-scale process demonstration to confirm performance results and economic estimates.

■ *EPRI Contact: Ralph Altman, (615) 899-0072*

New Clearinghouse on Environmental Externalities

One of the most complex and rapidly changing regulatory areas affecting electric utilities involves environmental externalities—the assignment of explicit economic value to certain environmental impacts, such as the emission of air pollutants. To help EPRI members keep up with the accelerating pace of activity in this field, a clearinghouse on environmental externalities has been added to EPRINET, the Institute's technology delivery information network.

The Environmental Externalities Clearinghouse maintains a state-by-state database of regulatory activity related to externalities, including current requirements, citations of important filings and orders, and details of implementation issues. A bibliography of the externalities literature provides references to books, research reports, and regulatory documents. Short summaries of key documents from the most recent literature are also presented.

In addition, the clearinghouse contains introductory background information on environmental externalities issues, together with summary analyses that can help users who are new to this field. A calendar of related activities notifies users of upcoming conferences and events, and a news shorts feature provides summaries of articles from recent journals and the trade press.

According to Victor Niemeyer, a program manager in the Integrated Energy Systems Division who helped create the new service, part of the problem facing utilities is that activities related to environmental externalities are in a constant state of flux. New requirements are added at various stages of implementation, and regulatory agencies are still sorting out their overlapping jurisdictions. The clearinghouse will provide utilities the most comprehensive and timely overview of the subject now available, from basic introductory information to the latest details of regulatory action in each state.

"Launching this clearinghouse on EPRINET represents an important experiment in technology transfer," says Niemeyer. "We have received a lot of requests for information on environmental externalities. Such information quickly gets out of date if you offer it just in printed form—which argues strongly for on-line electronic access. The clearinghouse is intended to be used on an as-needed basis by utilities, so we must follow future use patterns closely to ensure that it remains a worthwhile venture."

The Environmental Externalities Clearinghouse is being developed and maintained by Barakat & Chamberlin of Oakland, California. ■ *EPRI Contact: Larry Williams, (415) 855-2695. Barakat & Chamberlin Contact: Marjorie McRae, (510) 893-7800. EPRINET Help Desk: (800) 964-8000*

Nuclear Fuel Guidelines Aim at Defect-Free Core

The failure of nuclear fuel elements can have major impacts on plant operation and maintenance; it can lead to restrictions on reactor power level, for example, and increase the potential for radiation exposure of maintenance personnel. The recognition of such impacts has raised the issue of fuel reliability to new prominence in the nuclear industry. As part of this enhanced effort, guidelines have been developed and published (EPRI TR-100659) to help nuclear utilities establish their own fuel reliability programs and achieve "zero defect" reactor operation.

Since the late 1980s, the utility industry perception of what constitutes an acceptable level of fuel reliability has shifted substantially. In the past, it was not uncommon to operate for some time with cores known to contain a certain number of failed fuel rods. As the potential cost of fuel failure became more apparent, however, and as reactor operating practices began to change, utilities sought guidance in establishing programs to enhance fuel reliability.

An important response to this growing emphasis was the publication, in 1987, of an EPRI report (NP-5521-SR) recommending corrective actions following the detection of a fuel failure. The new fuel reliability improvement guidelines address the next step—establishing an overall program to prevent fuel failures from happening in the first place. These guidelines were developed through the collaborative efforts of EPRI, the Institute of Nuclear Power Operations, and experts from 11 individual U.S. utilities.

The guidelines are particularly timely because of an industry trend toward increased fuel duty, as utilities opt for extended reactor operating cycles, higher discharge burnups, and advanced fuel design features. In addition, changes in water chemistry due to plant aging can have implications for fuel performance. Unless accompanied by a program to improve fuel performance, such changes could increase the frequency of failures caused by existing mechanisms or result in new modes of failure. Using the new guidelines, utilities can develop their own policies and procedures aimed at the prevention of all fuel defects.

The guidelines address the needs of both management and technical personnel regarding a plan's development and implementation. One objective addressed is to define for senior management the scope and content of a utility-specific fuel reliability program. For plant managers, engineers, and operations personnel, the report delineates the practices that should be followed to ensure good fuel reliability.

Included are sections on fuel design, fabrication, receipt inspection and handling, plant cleanliness control, operations, water chemistry control, fuel integrity monitoring, operation with failed fuel, and fuel inspection and repair. A recurrent theme is the need for awareness and commitment by all program participants, with responsibilities clearly assigned to appropriate management or line personnel. ■ *EPRI Contacts: Rosa Yang, (415) 855-2481, and Odelli Ozer, (415) 855-2089*

Power Quality Testing Network Formed

Sensitive microprocessor components in today's electronic equipment are susceptible to slight electrical disturbances in the power supply. Such disturbances can make clocks go on the blink, scramble computer data, and stop automated industrial equipment. To further the industry's understanding of such problems, EPRI's Power Electronics Applications Center in Knoxville, Tennessee, has established the Power Quality Testing Network (PQTN).

The network manages power quality testing that is carried out by nonprofit agencies and universities and supported by individual utility sponsors. Member utilities or their customers can contact EPRI and request a PQTN evaluation of power-electronics-based devices—for example, power supplies in personal computers. The testing assesses how the equipment can be effectively connected to the utility system in the short run and identifies what manufacturers can do in the long run to improve product design.

Products may be redesigned to operate through short power disturbances instead of shutting off or to generate less interference with utility systems, which can itself cause power quality problems. Test results for a specific product will be provided directly to the manufacturer; combined, generic results will be used to create a database to help member utilities understand a product group's power quality attributes.

In April, PQTN began its first collaborative research project—an evaluation of the high-frequency ballasts used in fluorescent lights. These ballasts are extremely energy-efficient: a 75-watt incandescent bulb can be replaced with an electronic fluorescent compact that uses only 15 to 18 watts, yet delivers the same amount of light. However, not enough is known about the power quality disturbances that the electronic ballasts may generate or about how well they withstand the disturbances they receive. Tests on the ballasts are being conducted independently at multiple PQTN member labs.

Similar tests have begun on transient voltage surge suppressors (TVSSs), which are installed to protect electronic equipment from overvoltages and other problems. No standards have yet been set for TVSSs, and data from the PQTN tests will help both utilities and manufacturers understand their power quality characteristics and limitations. Initial results from the ballast and TVSS tests are expected by the end of this year. Future evaluations will focus on personal computers and adjustable-speed drives up to 10 horsepower. ■ *EPRI Contact: Marek Samotyj, (415) 855-2980*

Hydroelectric Systems

Concrete Gravity Dam Stability Analysis

by Douglas Morris, Generation & Storage Division

EPRI's Hydroelectric Generation and Renewable Fuels Program has developed a specialized code for concrete gravity dam stability analysis. The code, CG-DAMS, was designed to respond to the dam stability analysis requirements of the Federal Energy Regulatory Commission (FERC), which are set out in the commission's *Engineering Guidelines for the Evaluation of Hydropower Projects*. These guidelines were developed by FERC's Office of Hydropower Licensing to help the commission's technical staff evaluate dam safety and stability.

At five-year intervals, dam owners are required to reevaluate dam stability in light of current conditions and design criteria. Essentially, a stability analysis determines a dam's resistance to sliding on its foundation under three loading conditions: normal loading, flood loading, and seismic loading. Existing dams that do not meet the required shear safety factor for each condition are usually "tied down" with posttensioned anchors driven from the dam crest into the foundation. The average cost of stabilizing a dam with anchors is $2 million, but the actual cost can be higher by a factor of 10.

The FERC guidelines allow owners to adopt a variety of analytical approaches of widely ranging complexity. They also allow owners to use generic values for concrete-to-rock bonding strengths and for shear and tensile strengths of concrete, and to use linear uplift pressure distributions. In fact, owing to the guidelines' many assumptions and simplified concepts, analyses can be performed by slide rule or pocket calculator. The penalty is that in the majority of cases the results are very conservative and require more material for stability than necessary. Moreover, one EPRI site study found that the results could also overestimate structural stability, although the required safety factors were met at the dam being studied and safe operation was assured.

Because of the recognized overdesign aspects of the calculation, dam owners have recently started to use data taken at their sites, as well as data from strength tests on core samples of concrete and rock, in their analyses. This approach produces more-realistic stability results than the generic values do, and FERC now encourages owners to perform site investigations to acquire actual values.

CG-DAMS

EPRI's dam safety advisory committee is composed of representatives of EPRI member utilities, consulting firms, FERC, and the three major federal dam-owning agencies. It concluded that the use of finite-element analytical methods that allow the input of site-specific strength and other material parametric values would result in more-realistic dam stability assessments. General software programs with that type of capability existed, but they required a great deal of manipulation to model dams, foundations, and reservoirs. The preferred approach was to design a code suitable for a typical utility structural engineer, who might perform dam analyses only once every three to five years. To bridge the gap between finite-element methods and traditional analytical practices, EPRI sought to design a code that would provide as many automatic options as possible and would simplify data input.

CG-DAMS meets these specifications. The code allows users to model concrete as either a linear-elastic or a nonlinear material. Users can select a typical dam profile from a set of overflow and nonoverflow sections. Using information readily available from design drawings, they can customize the standard profile by entering dimensions such as dam height, crest width, downstream and upstream face slope angles, and drainage gallery location. The modeled profile can be analyzed with or without the foundation and the reservoir. The code can generate a finite-element mesh to suit all the modeled elements. If the dam section to be analyzed has a unique profile—for example, if it includes the powerhouse—the analyst can create that profile and generate a suitable mesh; however, this requires a higher degree of user experience.

Under the guidance of H. T. Tang of EPRI's Nuclear Power Division, the initial version of CG-DAMS was merged with ABAQUS-EPGEN, which provided the concrete constitutive model and the numerical analysis capability. The positive response of EPRI members to that version, which runs on a mainframe,

ABSTRACT *Under Federal Energy Regulatory Commission (FERC) guidelines, dam owners must evaluate the stability of their structures every five years. Because traditional approaches typically yield overly conservative stability estimates, EPRI sponsored the development of a computer code, CG-DAMS, to provide more-realistic assessments that reflect site-specific conditions. This finite-element code—which is available in mainframe, workstation, and personal computer versions—can be used to predict crack growth, shear, and stress under a variety of loads.*

encouraged the development of a personal computer version with additional modeling options. The PC version is independent of ABAQUS.

Users can input a wide variety of loads to CG-DAMS via input screens designed to EPRIGEMS criteria and similar in format to Macintosh and Windows screens. In addition to accounting for the gravity load of the dam, the code applies hydrostatic pressure distributions for headwater and tailwater levels and applies point loads for overflow loading on the crest and spillway buckets (Figure 1). It can simulate the effect of filling the reservoir on the dam structure and the foundation, automatically applying the reservoir load in steps to determine the stability at each level (Figure 2). Silt, backfill, and ice loads are also standard loading options.

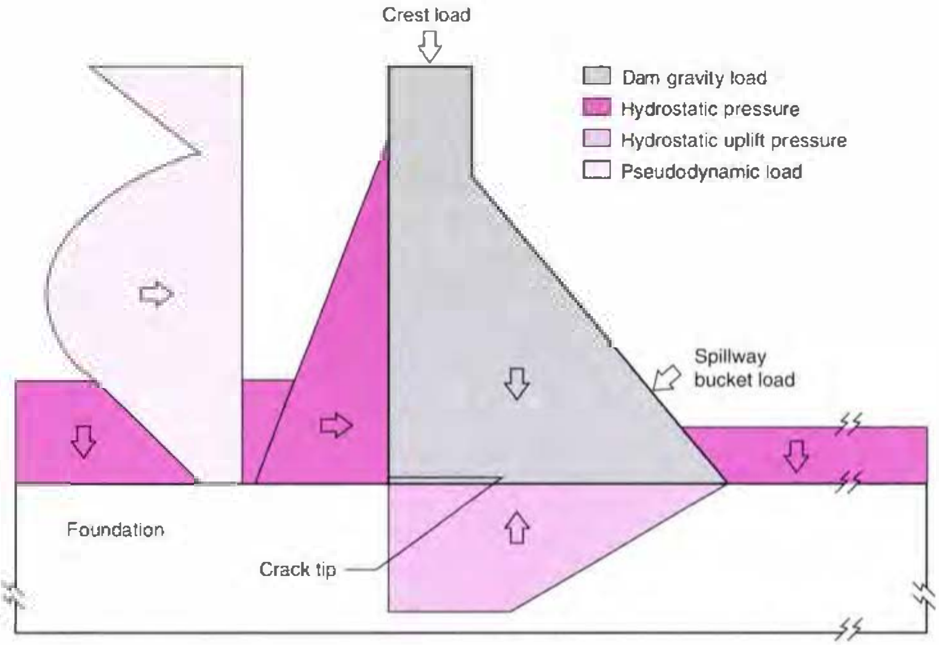
A major feature of the code is its ability to include thermal loads and directly couple the thermal response results to the stress analysis. The heat source can be atmospheric or, in the case of the heat of hydration of the curing concrete, internal. Users can assign temperatures to the dam and the foundation. The material properties required for modeling thermal loading include heat transfer coefficients, thermal conductivity, and thermal expansion; concrete creep compliance and the aging effect of temperature on the modulus of elasticity are optional.

Dynamic (seismic) loading can be simulated by using a pseudodynamic reservoir pressure loading routine developed by Professor Anil Chopra of the University of California at Berkeley, or by inputting a time-history record of actual or simulated earthquakes. The latter method currently is available only on the mainframe version of the code. CG-DAMS can also perform a frequency analysis, using the subspace interaction method to extract the structure's fundamental frequency.

Hydrostatic uplift pressure loads are applied at the interface of the dam and the foundation. The default option is a linear distribution or, if the dam has drains, a bilinear distribution. However, users can input alternative distributions, such as actual site measurements taken along a section. If the analysis determines that a crack will develop, the code automatically adjusts the uplift pressure to match the length of the crack as it grows. If the crack projects beyond the line of drains, the user can choose to follow FERC's assumption that the drains will no longer operate or can select other drain characteristics, such as those described in EPRI report TR-100345. Users can define a crack in the dam or the foundation by entering zero tensile strength for the designated area. The code automatically applies uplift pressure distributions in such cracks that are appropriate to their location and angle.

Users can add cracks in the foundation to represent rock joints, seams, and faults, and can subdivide the foundation into sections with different material properties to simulate different types of rock. Also, they can

Figure 1 CG-DAMS can account for a variety of loading conditions. A pseudodynamic loading routine simulates seismic loading against the upstream face of the dam. The code also models the effect of crack growth on hydrostatic uplift pressure at the interface of the dam and the foundation, automatically adjusting the pressure distribution along the length of a crack.



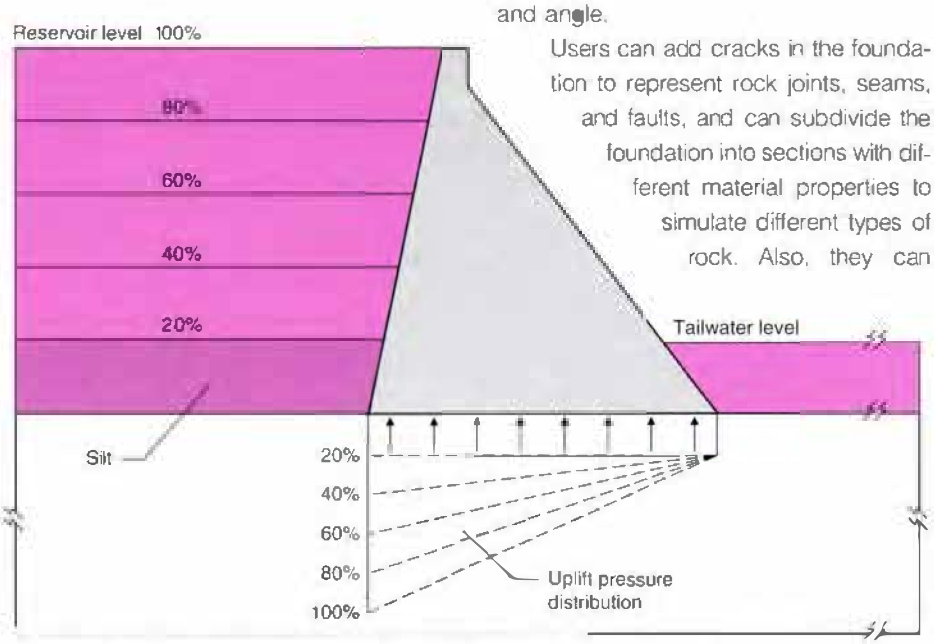


Figure 2 By applying the reservoir load in steps, CG-DAMS can simulate the effects of reservoir filling on a dam and its foundation—for example, the effects on uplift pressure at the dam-foundation interface. In the case shown here, at the 20% reservoir level the uplift pressure is evenly distributed along the interface; the filling of the reservoir results in greater uplift pressure closer to the dam's upstream face.

change the concrete-to-rock interface profile by entering the code's finite-element mesh generation routine.

CG-DAMS offers a variety of output tables and graphics. For example, the results of an analysis can include the length of a crack along the concrete-to-rock interface and the value of the shear safety factor. The code also provides stress profile plots (with uplift pressure included) and principal stress vector plots. It can present results for individual loads as well as results for the combined loads. It also plots dam stability response to dynamic loading versus time.

Other research

In conjunction with the development of CG-DAMS, EPRI investigated the operation of 17 dams across the United States that ranged in age, height, and foundation treatment and rock type. The researchers studied records of uplift pressure, headwater and tailwater levels, and ambient temperatures for the dams. Their objectives were to identify factors that influence uplift pressure distribution and to validate or improve the accuracy of the assumptions in the FERC guidelines. This knowledge will help dam owners better focus site investigations to obtain information about the parameters important to stability analysis.

Dam designs are commonly based on the assumption that the rock mass behaves like a porous medium. Unless the joint spacing is small, uplift pressure distribution is controlled by the length and relative permeability of the rock joints that intersect to form the flow path beneath the dam. Field data from the study have shown how the aperture size of the joints defines the shape of the uplift pressure distribution. As the loading on a dam changes, the loading on the foundation changes, causing the rock joints to open or close. When seasonal temperature increases cause a dam's downstream face to expand, the foundation loading changes. The seasonal temperature effect at some of the sites studied was much greater than expected. It is possible that changes in uplift resulting from this phenomenon had been erroneously attributed to flood loads from the spring runoff.

Records showed that at some of the sites uplift pressure has a linear relationship to changes in load. At other sites, the association was found to be quadratic or exponential. Finite-element analysis using a computer model demonstrated that these relationships depend on rock joint apertures. Tight or grouted joints result in a nonlinear relationship between headwater level and uplift. This knowledge will help dam owners use uplift pressure measurements for seasonal flood levels to project values for abnormal flood levels, such as the probable maximum flood. FERC had been reluctant to permit such extrapolation because of the variation in behavior at different sites, but it has now relaxed the guidelines as a result of the EPRI studies.

EPRI has completed a numerical model, CRFLOOD, that predicts flow and uplift pressure distribution in a rock joint or in a crack in concrete. The model was verified by laboratory tests on a specimen with dimensions equivalent to those at actual sites. Results from CRFLOOD for different entry heads, crack apertures, and drain diameters confirmed the findings concurrently obtained in the study of the 17 dam sites. In the future, CRFLOOD will be merged with CG-DAMS to model the combined effect of flow and stress in cracks. CRFLOOD is also under consideration for use in dam stability analyses with an improved model of foundation rock joint configurations.

Members of EPRI's dam safety advisory committee have been instrumental in getting their organizations to test CG-DAMS and CRFLOOD during their development, and these reviews have resulted in major improvements that have boosted the codes' practicality. In addition, two EPRI members have submitted test cases to FERC so that it can develop procedures for reviewing stability analyses that use the EPRI codes.

Residential Program

Developments in Line-Voltage Thermostats

by John Kesselring, Customer Systems Division

A thermostat is a temperature-sensitive on/off switch used to control a heater or an air conditioner. For heating, the thermostat signals the heater to turn on when the temperature drops below the set point chosen by the occupant. When the room temperature (as measured by the thermostat) reaches the set-point temperature, the thermostat signals the heater to turn off. Three basic elements make up this simple feedback loop: a temperature sensor, a device for switching the heater on and off, and a means by which the occupant can control the set point.

Line-voltage and low-voltage thermostats are the two most commonly used types of thermostat. A line-voltage thermostat is connected in series with the heater and the line voltage—the voltage in the electrical circuit for the building. It controls the heater simply by switching the line voltage on and off. A low-voltage thermostat is connected to a low-voltage (24-V) electrical relay. This relay, rather than the thermostat itself, energizes and deenergizes the heater. The low-voltage thermostat is by far the most common type of control for central forced-air (electric or gas) residential heating and cooling systems, but it is too expensive for use in zoned applications, in which each room or zone is heated by an independent unit.

Bimetal-strip line-voltage thermostats

In many parts of the country, baseboard electric resistance heaters are the residen-

ABSTRACT *A thermostat that provides reliable, accurate temperature control is the key to a comfortable, efficient space-heating system. The lack of a commercially available line-voltage thermostat that is affordable and performs well has been a significant factor in limiting the comfort and popularity of zoned residential electric heating systems. With EPRI support, two manufacturers have developed innovative, electronics-based line-voltage thermostats that offer a cost-effective control option for creating a comfortable environment with zoned electric heat. These thermostats also may help reduce energy consumption.*

tial heating option with the lowest first cost. Intended for use in zoned systems, these heaters—like kickspace and radiant ceiling heaters—offer other advantages as well: they are mechanically simple, highly durable, and very quiet. Moreover, zoned systems give occupants the opportunity to reduce energy use by lowering thermostat settings in unoccupied rooms. Nevertheless, zoned electric heating systems are often regarded as uncomfortable, inefficient, and expensive to operate. Largely responsible for this perception is the device commonly used to control the heating units—the line-voltage thermostat.

Electrical contractors purchase more thermostats for residences than any other consumer group, and they strongly influence the market for line-voltage thermostats. Building codes rarely specify the type or quality of thermostat to be installed. To enhance the attractiveness of their bids on work in residences designed for zoned heating, contractors typically procure the least expensive thermostats, namely, built-in or wall-mounted bimetal-strip line-voltage thermostats.

The bimetal-strip thermostat is a very simple mechanism. The heart of it is an element composed of thin sheets of two different metals that are bonded together. The metals expand or contract at different rates when the room temperature changes. Thus, as the room cools off, the bimetal strip bends down toward an electric switch and eventually makes contact with it, turning the heater on. When the set point is reached, the strip springs away from the switch, turning the heater off.

A recent EPRI study (RP2034-29) has made it clear that the lowest-cost bimetal-strip line-voltage thermostats perform very poorly. The strips adjust slowly to changes in room temperature, and internal heating of the wires often makes it difficult to maintain a set-point temperature. Even shortly after installation, these thermostats generally do not maintain stable temperatures, and their performance degrades with time. As a result, users do not get the full benefits of an efficient zoned electric heating system.

For zoned applications, the only alternatives to low-cost, bimetal-strip units to date have been considerably higher priced electronic or electromechanical line-voltage thermostats. To improve the quality of zoned heating, EPRI recently sponsored the development of high-performance electronic line-voltage thermostats that are relatively inexpensive.

Thermostat performance

The performance of a thermostat is judged by how closely it maintains the room temperature at the set point. This depends, in turn, on three key parameters: deadband, cycle frequency, and droop. Performance may also be influenced by the physical placement of the thermostat (relative to windows, outside walls, or the heater itself) and by the quality of the installation (overtightening of mounting screws may damage bimetal-strip thermostats).

Deadband is the temperature range in which the thermostat sends no control signal to the heater. This range corresponds to

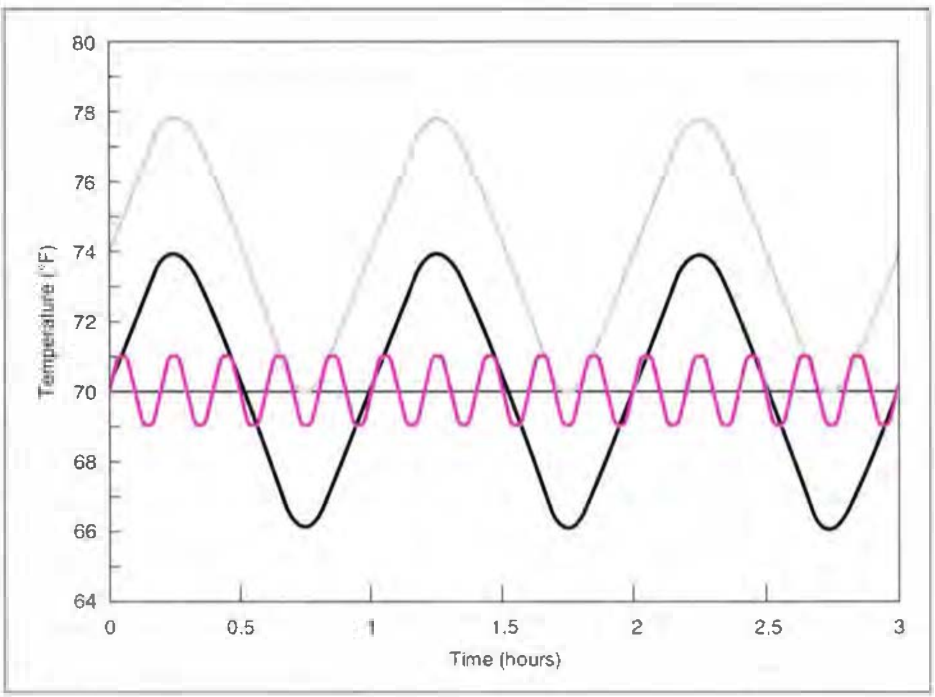


Figure 1 Temperature control around a 70°F set point. A thermostat with a large deadband allows the room temperature to swing widely (black curve). In response, occupants may raise the set point so that the temperature never dips below the desired 70° (gray curve), thereby increasing energy consumption. The precise control afforded by new, electronic line-voltage thermostats, which have a 2° deadband (color curve), promises energy savings as well as increased comfort.

Figure 2 High-performance, low-cost line-voltage thermostats: Honeywell's prototype (left) and PSG Industries' basic residential model (right). These electronics-based thermostats, developed with EPRI support, will help maximize the benefits of zoned residential electric heating systems. Advanced features will include programmability and setback capability.

the difference between the temperature at which the thermostat switches the heater on and that at which it switches the heater off. Deadband is a function of how sensitive the temperature sensor is to changes in room temperature. To keep occupants comfortable, the deadband should be narrow, 2–4°F (2°F is the smallest difference to which people are normally sensitive).

Figure 1 illustrates the importance of deadband. The least expensive thermostats generally have the widest deadbands. In zoned applications, these thermostats may allow the room temperature to swing widely. Given wide temperature swings, a typical occupant may feel discomfort and in cold weather may raise the set point so that the lowest temperature in the room is tolerable. In that event, the minimum temperature in the cycle is equal to the desired temperature, and the average room temperature is increased. A thermostat with a smaller deadband could increase occupant comfort and at the same time save energy, as testing by Portland General Electric Company has shown. In carefully controlled situations involving the same customers in the same residences, EPRI plans to compare customer electricity consumption on a common degree-day basis when a bimetal-strip thermostat is used and when a high-performance line-voltage thermostat is used.

Cycle frequency, usually measured in cycles per hour, indicates how many times the thermostat turns the heater on and off. Each on/off/on sequence delimits one cycle. In general, electric heaters should cycle four or more times per hour in order to keep room temperature near the set point. To increase cycle frequency and reduce deadband, many bimetal-strip thermostats include an anticipator—a very small resistance heater located close to the temperature sensor inside the thermostat. Used to minimize overshoot, it "anticipates" the time when the room temperature will reach the set point and shuts the heater off, letting the temperature coast up to the set point as the residual heat in the heating system is released into the room.

Droop is a reduction in room temperature that typically occurs when the wires inside a thermostat are heated by current passing through them to the heater. If the temperature sensor is not thermally insulated from these wires and the anticipator, the thermostat operates as if the room temperature were higher than it actually is. As a result, the heater is switched off prematurely and the set-point temperature is in effect reduced. Long duty cycles, which are relatively common in cold weather, are a leading cause of heat buildup in thermostats. Thus, a comfortable temperature setting in mild weather might result in significant droop in cold weather, leading occupants to increase the set point (and cause further droop). By thermally insulating the sensor and by putting openings in the thermostat casing to keep the device well ventilated, thermostat manufacturers can reduce droop.

Electronic line-voltage thermostats

With EPRI support under RP2731-12 and -13, Honeywell and PSG Industries have each developed an electronics-based line-voltage thermostat that performs well and promises to be relatively inexpensive (Figure 2). Both the thermostats meet EPRI-specified performance requirements: they operate with a 2°F deadband, reduce droop to less than 2°F, and cycle five or more times an hour if necessary.

For temperature sensing, both thermostats use thermistors—solid-state sensors that undergo changes in electrical resistance as temperature changes. The thermistors are used to measure temperature at set intervals (e.g., every 5 seconds). The thermostats are well ventilated, and in each the thermistor is insulated from the wiring. Earlier electronic line-voltage thermostats used thermistors too, but they needed several components (including bridge circuits, signal amplifiers, and sophisticated voltage regulators) to prevent erroneous readings. The Honeywell and PSG thermostats use fewer components and are designed for easy assembly; prices for them should be well below prices for other high-performance line-voltage thermostats.

In PSG's thermostat, thermistor resistance is converted into a frequency and forwarded to a microprocessor, which is programmed to decode the signal, compare it with the set point and other data, and respond in a variety of ways. The microprocessor sends output to the temperature display, to a relay for heater switching (if necessary), and to a time delay, which serves an anticipator-like function, switching the heater off and letting residual heat in the heater bring room temperature up to the set point. The microprocessor also has multistaging capabilities for use with appropriate equipment: it can change fan speed in multispeed fan-forced heaters, and in heaters with second-stage heating elements, it can turn off the second-stage element at 3°F below the set point. Further, the thermostat can be connected to a motion and light detector, whose signal will trigger a heating cycle if the room temperature is below the set point.

PSG's electronic line-voltage thermostat has recently become commercially available, and a user-programmable model will soon go on the market. The programmable model will include a setback function that enables users to save energy when a room is unoccupied by adjusting the set point—lowering it during heating periods and raising it during cooling periods. PSG is exploring the use of its thermostat circuitry for temperature control in several appliances, including water heaters and through-the-wall air conditioning and heating systems.

Honeywell's new, low-cost line-voltage thermostat was jointly developed by the Honeywell Sensor and System Development Center in Minneapolis and Honeywell Limited of Canada. It uses a patented "cool switch" power-switching module; a power-stealing and control module that facilitates two-wire installation and increases retrofittability; and a compact design that enables high-volume, snap-together assembly and easy calibration while taking thermal characteristics into account. Thermostat prototypes have been life-cycle tested, and development is continuing. Commercial production is expected by the summer of 1993.

To provide high performance at low cost, Honeywell has initially focused on control functions in its new line-voltage thermostat. Later models will incorporate functionality enhancements, such as setback capability, programmability, digital displays, and control buttons—features that are already included in other Honeywell thermostats. Some Honeywell thermostats also already include the corporation's patented light- and motion-based thermostatic control.

The price of the new thermostats will vary with thermostat features, the level of distribution, and the manufacturers' marketing strategies. The least expensive ones are expected to cost roughly $12 more apiece than bimetal-strip thermostats, today's lowest-cost option. The new thermostats can be installed quickly and are designed for use with older baseboard and radiant heating systems as well as with new systems. PSG and Honeywell believe that there is a large retrofit market for the new thermostats, and EPRI expects the devices to help utilities retain their existing share of the home heating market. Utilities with aggressive demand-side management programs may well offer rebates or other incentives for retrofitting or installing the thermostats.

Land and Water Quality

Comanagement of Low- and High-Volume Utility Wastes

by Ishwar P. Murarka and John W. Goodrich-Mahoney, Environment Division

ABSTRACT *EPRI studies at two power plant sites show that comanagement—the practice of comingling, in utility disposal ponds, low-volume noncombustion wastes (such as boiler-cleaning and water purification wastes) with high-volume wastes from coal combustion—does not contaminate groundwater or soils with hazardous trace elements. The Environmental Protection Agency currently classifies high-volume combustion wastes as nonhazardous. The extensive field data collected by EPRI are relevant for the EPA's future regulatory determination of whether low-volume noncombustion wastes also are nonhazardous and therefore whether comanagement may continue.*

Electric utilities produce several wastes or by-products associated with the combustion of fossil fuels. The greatest volumes of waste are generated from the control of flue gas particulate matter and emissions of sulfur oxides. These wastes, produced continuously during the combustion process, are generally referred to as high-volume combustion wastes; they include bottom ash, fly ash, and flue gas desulfurization sludge. In addition, several low-volume wastes from noncombustion activities—including boiler-cleaning liquids, demineralizer regeneration wastes, water treatment sludges and brines, and equipment-cleaning wastes—are produced on a periodic basis. At many power plants, low- and high-volume wastes are comanaged in ponds or landfills (Figure 1).

In a 1988 report to Congress, the Environmental Protection Agency (EPA) concluded that high-volume combustion wastes are generally nonhazardous and that the electric utility industry's disposal management practices for these wastes are protective of the environment and human health (*Wastes from the Combustion of Coal by Electric Utility Power Plants*, EPA/530-SW-88-002, February 1988). The EPA noted the lack of data on the environmental effects of comanagement, however, and expressed concern that some low-volume wastes may exhibit hazardous characteristics. There-

Figure 1 Codisposal of low-volume noncombustion wastes (bottom pipe) and high-volume combustion wastes in an ash pond. EPRI has gathered environmental data on this utility practice, called comanagement, for use in regulatory review.

fore, the agency stated its intention to consider, on the basis of further study and information obtained during the public comment period, whether low-volume waste streams should be regulated under the hazardous waste provisions of the Resource Conservation and Recovery Act. The two low-volume wastes of greatest concern to the EPA are boiler-cleaning and water purification wastes. If the agency were to regulate these and other low-volume wastes as hazardous, the utility industry would have to end its practice of comanaging low- and high-volume wastes.

To provide the EPA with data necessary for making a final determination, EPRI conducted environmental performance assessments at two coal-fired power plants that comanage low- and high-volume wastes in ponds: L-site in the southeastern United States (EPRI report EN-7545) and C-site in the Midwest (TR-100955). The studies focused on the subsurface environment to determine if comingled low-volume wastes have a discernible effect on groundwater downgradient from the ash ponds. During the two years of field sampling and analysis, the researchers collected data defining waste characteristics, the leachates that formed, their migration into the underlying subsurface, and their effects on groundwater quality. By sampling upgradient groundwater, the researchers also established the ambient water quality.

Low-volume waste characteristics

The term *low-volume waste* is typically applied to noncombustion wastes produced at a power plant during such activities as equipment maintenance and water treatment. The most common examples include boiler and cooling-tower blowdown, water treatment sludges, demineralizer regenerant, boiler-cleaning wastes, pyrite rejects, coal pile runoff, and floor and yard drain collection sump effluents. These wastes are of diverse origin and differ widely in volume and chemical composition; many of them are produced intermittently as a result of rainfall or scheduled maintenance activities.

The low-volume wastes causing the greatest regulatory concern are boiler-cleaning wastes. Although boiler-cleaning wastes generally contribute less than 1% to the total waste volume, they can contain relatively high concentrations of copper, iron, cadmium, chromium, lead, and other metals, as well as chemicals from the cleaning solutions, such as nitrates, ammonia, and citrates. Untreated boiler-cleaning wastes occasionally exhibit hazardous waste characteristics, most notably corrosivity and concentrations of cadmium, chromium, or lead that exceed regulatory levels. However, codisposed boiler-cleaning and high-volume wastes do not exhibit hazardous characteristics.

The low-volume wastes with the largest annual volumes (1 to 20 million gallons) have the lowest concentrations of dissolved solids and are unlikely to have a measurable impact on the environment when codisposed. These wastes include boiler blowdown, demineralizer regenerants, fireside wash water, and floor and yard drain effluents. Within this group, demineralizer regenerants have the greatest total-dissolved-solids content. Demineralizer regenerants are produced during the removal of natu-

Table 1
CHEMICAL CONSTITUENTS AT OR BELOW BACKGROUND LEVELS IN DOWNGRADIENT WELLS

At both sites	
Aluminum	Lead
Ammonia	Manganese
Antimony	Molybdenum
Arsenic	Nickel
Barium	Nitrite/nitrate
Beryllium	Phosphate
Cadmium	Selenium
Chloride	Silicon
Chromium	Silver
Cobalt	Sulfide
Copper	Thallium
Iron	Thiourea
At L-site only	
Boron	Potassium
Bromide*	Sodium
Fluoride	Vanadium*
At C-site only	
Magnesium	

*Not analyzed at C-site.

rally occurring minerals—calcium, magnesium, sodium, and sulfate—from already clean water to produce ultrapure water for use in boiler tubes. Since these minerals are also present in high-volume wastes, it would be difficult to isolate the contribution of regenerant waste to changes in groundwater quality.

Pyrite rejects and coal pile runoff, particularly from the more acidic eastern bituminous coals, also can add trace metals to the ash pond leachate. When oxygen and moisture are present, pyrite oxidation occurs, lowering the aqueous pH and releasing iron, sulfate, and other constituents. Coal pile runoff can contain high concentrations of copper, zinc, magnesium, aluminum, chloride, iron, sodium, and sulfate.

Table 2
CHEMICAL CONSTITUENTS ABOVE BACKGROUND LEVELS IN DOWNGRADIENT WELLS

	Mean Groundwater Concentration (mg/L)		
Constituent	Upgradient	Ash Pond	Downgradient
At L-site			
Calcium	6	335	26
Magnesium	2	45	11
Strontium	0.03	0.6	0.2
Sulfate	4	1630	103
At C-site			
Boron	<0.6	11	6
Calcium	93	144	123
Fluoride	0.1	0.2	0.4
Potassium	<3	89	9
Sodium	14	44	61
Strontium	0.1	0.8	0.4
Sulfate	73	220	350

Note: Concentrations were measured in groundwater samples from wells upgradient of, below, and downgradient of the ash ponds. The upgradient results established the constituents' background levels.

L-site study

L-site is a 60-acre pond system serving a 400-MW coal-fired plant. The disposal facility consists of two unlined settling ponds that have been used for waste comanagement since 1973. Approximately 30,000 cubic yards of fly ash and bottom ash from eastern bituminous coal are sluiced to the ponds annually, as well as most of the plant's low-volume wastes. In the L-site study, the researchers installed and monitored 24 wells and piezometers and collected 70 geologic core samples to evaluate the environmental effects of comanaging low- and high-volume wastes.

The waste disposal ponds lie over a series of bedrock valleys filled with highly permeable alluvial sediments and saprolite, which make up the shallow aquifer. The saprolite is produced by the in-place chemical weathering of the metamorphic bedrock. The horizontal alignment of the platy mica minerals in the saprolite greatly influences the aquifer characteristics, yielding horizontal hydraulic conductivities two to three orders of magnitude higher than the vertical hydraulic conductivities.

Between 20% and 35% of all the water entering the pond system discharges through its base into the shallow groundwater aquifer. The groundwater then moves horizontally through the alluvium and saprolite to a nearby river. Its velocity is highly variable; the mean value is just under 1 foot per day. Geochemical analysis of soil cores indicated a low attenuation capacity in the coarse-grained aquifer.

Groundwater samples were collected from monitoring wells located upgradient of, below, and downgradient of the ash ponds. In samples from the downgradient wells, nearly all the constituents analyzed either were at or below detection limits or did not significantly differ from background (i.e., upgradient) concentrations (Table 1). The only analytes with elevated concentrations in the downgradient well samples—calcium, magnesium, strontium, and sulfate—are generally associated with high-volume combustion wastes (Table 2). These analytes are also common constituents of groundwater and are frequently found in concentrations higher than those observed at L-site. Sulfate is the only one of the four with a published federal drinking-water standard—namely, a secondary standard of 250 mg/L. Its concentration in the downgradient wells was less than one-half that amount. Analysis of soil cores showed no evidence that elements from the waste were accumulating in the soils either below or downgradient from the ponds.

The soil and groundwater analyses found no measurable impact attributable to the low-volume wastes at L-site. None of the regulated trace elements were elevated in the downgradient wells. Increased iron and sulfate concentrations and low pH were observed within and directly beneath the ponds, indicating that some localized pyrite oxidation may be occurring. However, no pyrite oxidation products were found in the downgradient wells. The oxidation products either attenuate in the aquifer matrix or have limited mobility because of the relatively stagnant groundwater flow in that part of the site.

C-site study

C-site is a 280-acre pond system serving a 1000-MW coal-fired plant. The site comprises two unlined settling ponds that began operation in 1970 for the disposal of low- and high-volume wastes. Nearly 500,000 tons of fly ash and bottom ash derived from bituminous coal are sluiced to the ponds annually, along with most of the plant's low-volume wastes. The researchers at C-site installed and monitored 36 wells and piezometers.

The C-site ponds are located in an old river meander over a coarse-grained alluvial aquifer. The ponds have created a groundwater mound, resulting in radial flow away from the facility. Nearly 90% of all inflow to the pond system discharges to the shallow alluvial aquifer. The groundwater velocity is very high, reaching 340 feet per day in the pebbly sediments near the northeast corner of the secondary ash pond. The attenuation capacity of the aquifer material is relatively low.

At this site, as at L-site, the comanagement of low-volume wastes with ash has not had a measurable impact on downgradient groundwater quality. Groundwater sampling showed that most analytes either were at or below detection limits or were statistically the same as background (upgradient) concentrations (Table 1).

The seven analytes with elevated concentrations in samples from the downgradient wells—boron, calcium, fluoride, potassium, sodium, strontium, and sulfate—are common groundwater constituents and are generally associated with high-volume ash (Table 2). The fluoride level was an order of magnitude below the federal primary drinking-water standard. The sulfate level was slightly above the federal secondary drinking-water standard of 250 mg/L. Trace metals associated with boiler-cleaning wastes were not elevated in the downgradient wells. Very low concentrations of chromium (<12 µg/L) were measured in groundwater from wells immediately adjacent to the ash ponds. Because the researchers did not observe chromium in any other groundwater samples, they concluded that it probably came from the geologic strata in which the wells were screened.

Environmental impacts of comanagement

The L-site and C-site investigations found no groundwater impacts uniquely attributable to the disposal practice of comanaging utility low-volume wastes with coal ash. Despite the high groundwater velocity and relatively low attenuation capacity at both sites, none of the hazardous trace elements present in the low-volume wastes had migrated into the groundwater after more than 17 years of operation. These results are consistent with previous EPRI laboratory research on the equilibrium geochemical processes that control the leaching and attenuation of trace elements in the environment.

These studies have investigated whether the comanagement of utility low- and high-volume wastes is an environmentally sound disposal practice. The EPA is likely to proceed with regulatory determination in 1993, and the L-site and C-site studies provide up-to-date, extensive field data for assessing the environmental performance of comanagement.

Fossil Plant SO_2 Control

FGD Economics

by Paul Radcliffe, Environment Division

In developing plans for complying with the 1995 Phase 1 deadline of the 1990 Clean Air Act Amendments (CAAA), utilities have been challenged to minimize the cost impact while dealing with a broad spectrum of legal, political, environmental, marketing, and technical issues. A cost-effective compliance strategy requires up-to-date, accurate, and objective cost information on alternative sulfur dioxide (SO_2) control technologies. The proper choice of a flue gas desulfurization (FGD) system will save a utility millions of dollars in initial capital outlay alone. Pollution control systems can account for up to 40% of the capital cost and 35% of the operating cost of new plants, and costs can be considerably higher when retrofitting FGD at existing plants.

Recognizing the need for objective and up-to-date information on the options available for SO_2 control, EPRI has completed technical and economic evaluations of 28 FGD processes, including both wet and dry technologies. The full results of these evaluations have been published in EPRI report TR-017193 (two volumes). In addition, a computer model for estimating site-specific costs (FGDCOST) has been released. With this model, users can tailor EPRI's published FGD cost estimates to their own installations, either new or retrofit.

ABSTRACT *With the passage of the 1990 Clean Air Act Amendments, utility planners are busy developing strategies for reducing emissions of sulfur dioxide. Working with a utility project advisory group, EPRI has updated technical and economic evaluations for 28 flue gas desulfurization processes, incorporating up-to-date information on the technical merits, capital requirements, and operating and maintenance costs of commercially viable FGD technologies. Also available is a new computer model that allows utility planners to make site-specific FGD cost estimates with increased accuracy.*

Cost estimates

The 28 processes evaluated fall into three categories: wet scrubbing, dry injection, and sulfur recovery. The wet scrubbing processes yield a by-product that contains substantial moisture. Typically these by-products are disposed of, and they may require dewatering before disposal. Also included in this category is the limestone process that produces gypsum of wallboard quality, suitable for sale. The reaction products from the dry injection processes (including spray drying) are collected in a dry form with the fly ash. In the recovery processes, sulfur is recovered from the flue gas in the form of elemental sulfur, sulfuric acid, or liquid SO_2.

Figure 1 shows current capital cost estimates for 25 of the 28 processes evaluated, and Figure 2 shows levelized control costs (assuming no inflation) per ton of SO_2 removed. (For the remaining three processes, costs were developed for special cases and are discussed below.) These cost estimates are for a moderately difficult retrofit situation and do not include plant modifications beyond the FGD system, such as stack relining/rebuilding and particulate control upgrades to accommodate the FGD system. Site-specific retrofit factors have a significant impact on costs. (The published evaluations present costs for new installations as well as for moderate retrofits.)

The cost estimates in Figures 1 and 2 are based on a single 300-MW unit, 2.6% sulfur coal, and two operating absorber modules plus one spare. This design basis is different from the basis used in previous EPRI FGD evaluations, which were developed for new plant sites, 500-MW units, 4.0% sulfur coal, and three absorber modules plus one spare. The lower-sulfur coal used for the current estimates is more typical of the coals being burned today. Engineering requirements have been reduced to reflect the experience and knowledge gained from the first generation of scrubbers. The maturation of FGD technology has led to simplified, more standardized designs and hence to reduced contingency fees. Because of the reduced unit size and correspondingly shorter construction period, the allowance for funds used during construction (AFUDC) is lower.

Technical and economic evaluations were also performed for three processes that are targeted for specific applications: two dry injection processes—NaTec dry sodium injection and HYPAS—and Passamaquoddy, a wet process that produces a calcium carbonate by-product. The cost estimates given here are for the moderately difficult retrofit case and are in 1990 dollars. The NaTec evaluation used a low-sulfur (0.48%) coal, as specified by the vendor because of the high cost of the soda reagent, and assumed a 300-MW unit and 50% SO_2 removal. The resulting capital cost was

Figure 1 FGD capital cost estimates for a moderately difficult retrofit (1990 dollars). The estimates assume a 300-MW unit, 2.6% sulfur coal, and—except as noted in parentheses for certain dry processes—SO_2 removal of 90%.

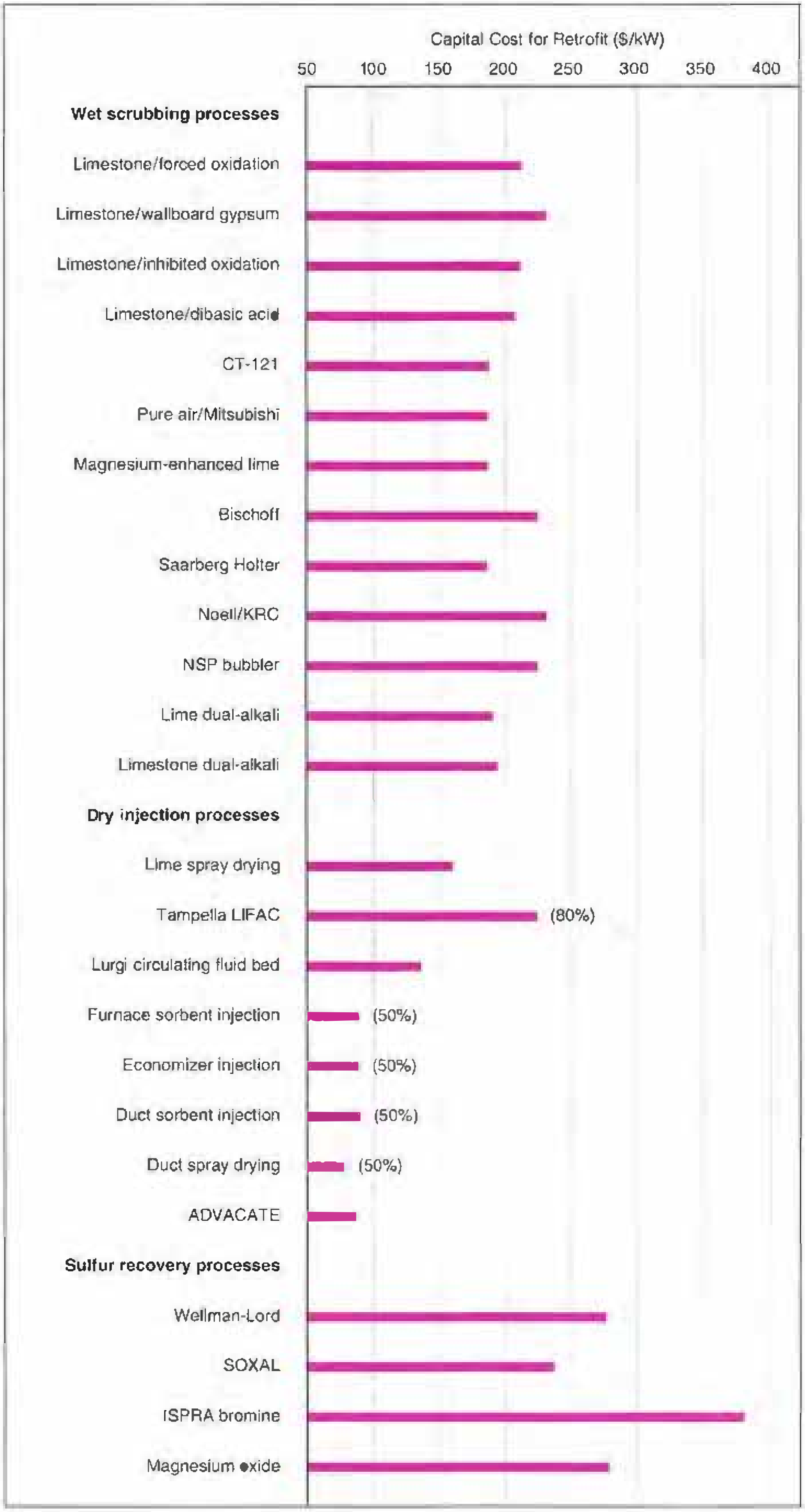
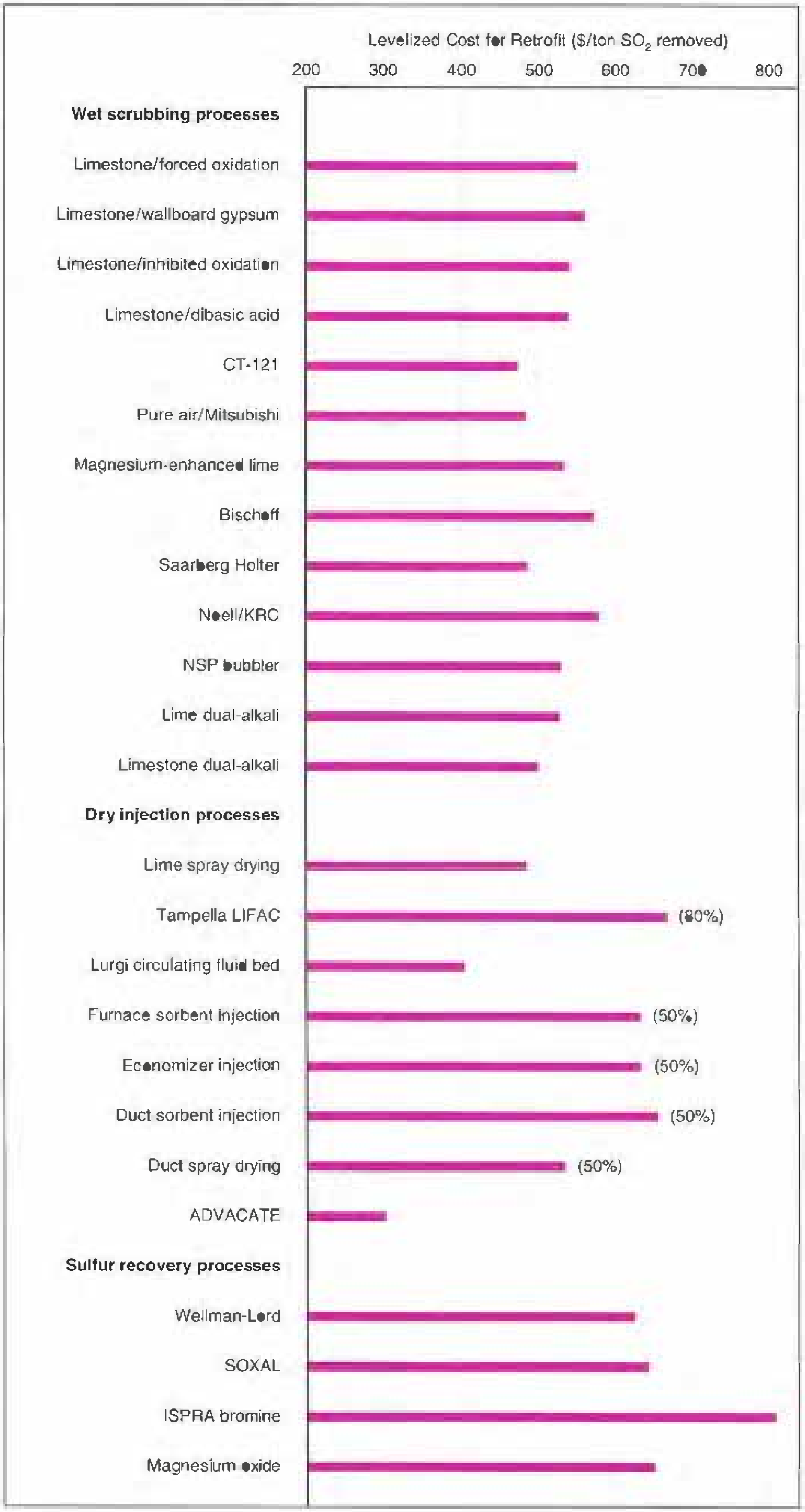


Figure 2 Levelized control costs for a moderately difficult retrofit—levelized over 15 years, constant 1990 dollars (no inflation). The estimates assume a 300-MW unit, 2.6% sulfur coal, and 90% SO_2 removal (except as noted in parentheses).



$50/kW, and the levelized control cost was $1500/ton of SO_2 removed. The HYPAS evaluation used coal with a sulfur content of 1.5% and assumed 60% SO_2 removal; for a 300-MW retrofit, the capital cost was $130/kW and the control cost was $974/ton SO_2. The Passamaquoddy recovery scrubber was evaluated for a 100-MW plant, which is in the range of its target market. The analysis used 2.6% sulfur coal and assumed 90% SO_2 removal. The resulting capital cost was $480/kW, higher than for other processes because of the smaller unit size. The control cost was $707/ton SO_2.

Among the more important conclusions that can be drawn from the evaluations to date are the following:

- Intense competition between system and component suppliers is serving to control FGD costs, which are lower than previously expected. Increasing demand in response to the CAAA could result in a seller's market, with higher prices; however, penetration from overseas suppliers will tend to dampen that impact. The highest demand is likely to occur in 1996–1997 in response to Phase 2 of the legislation.
- Costs per ton of SO_2 removed are very close for many of the conventional, wet scrubbing technologies.
- Compared with wet FGD, dry injection processes generally have lower capital costs but higher costs per ton of SO_2 removed.
- Design simplification can save more than 30% of the capital cost of conventional FGD.

Levelized control costs per ton of SO_2 removed are higher for most of the dry injection technologies because of their lower SO_2 removal capabilities and higher reagent costs. The dry injection technologies require much less capital, but they suffer from higher operating costs as a result of greater reagent consumption and cost. These technologies carry relatively more risk because they are under development. Still, they may be a practical choice for older, smaller units with limited space for retrofitting wet FGD.

EPRI's cost estimates were developed just before the passage of the CAAA, in what could be considered a buyer's market. With a large number of buyers entering the marketplace, it is possible that demand could shift, creating a seller's market. Approximately 15,000 MW of FGD retrofits have been ordered to date in response to Phase 1 of the CAAA. Prices could rise as demand on system and component suppliers increases. The magnitude of the impact is difficult to quantify and will depend substantially on the type of FGD process under consideration. Increased market demand could change both the absolute and relative costs of processes. Site-specific retrofit factors also will have a significant impact on costs.

Utilities would be wise to proceed with planning and retrofit cost studies now for Phase 2 compliance in order to avoid the anticipated seller's market in 1996–1997, when orders will be placed for the Phase 2 deadline. Cost increases should be restrained to some degree by the penetration of suppliers from overseas—suppliers who have been active in the European and Japanese markets, where stringent acid rain retrofit programs have been completed.

The final report on the processes examined to date includes commercial and technical evaluations, as well as cost estimates, and should help utilities make informed choices when screening alternative FGD technologies. Each process evaluation includes a brief overview of the process and chemistry, major design criteria, a flow diagram, a material balance, a list of relative advantages and disadvantages, the status of commercial development, capital and levelized cost summaries, sensitivity curves for principal input parameters, and a list of major equipment. EPRI is considering additional processes for evaluation.

Cost-saving concepts

A parallel project (RP2873-1) has investigated ways to control and minimize the cost impacts of retrofitting FGD at existing plants (EPRI report TR-100310). This effort has identified cost- and space-saving concepts that can be applied today in retrofit FGD systems without compromising performance and reliability.

These design concepts include the use of larger absorber modules, wet stack operation (no reheat), performance-enhancing additives, improved materials of construction, and simplified dewatering techniques. Compared with conventional wet FGD systems, advanced designs that incorporate these features can achieve savings of 30% in capital costs and savings of 25% in operating and levelized control costs, without loss of reliability.

FGDCOST

A computer model for estimating FGD system costs has been released that can help utilities tailor EPRI's generic cost estimates to specific plant sites. This menu-driven model, FGDCOST, features a spreadsheet template (one spreadsheet for each technology) that uses internally stored design information to enable users to readily estimate capital, operating and maintenance, and total levelized costs for both new and retrofit applications. The model computes costs by using site-specific data entered by the user and default values for the selected FGD process. User inputs specify economic criteria, boiler and coal characteristics, site conditions, and adjustments for retrofit difficulty.

Sensitivity analyses can be performed for variations in utility economic and design criteria, as well as for site-related alternatives. The model can be used to identify the relative importance of various cost elements, such as equipment, energy, manpower, and reagent. The spreadsheet format provides an easy way to examine alternative configurations and test sensitivities to changes in input parameters. User input can be saved as a worksheet file that is retrievable for use in subsequent runs.

Over 100 EPRI member utilities have used FGDCOST in their compliance planning. Utilities in three states have reported FGDCOST results within 5% of their final vendor quotes (in one case, within 0.3%). One utility that used FGDCOST came closer to its vendor quote than did a detailed estimate by its architect/engineer.

The new model takes the place of RETROFGD, a computerized FGD cost estimating code released by EPRI in 1987. With the assistance of a software developer, EPRI is developing an EPRIGEMS version of FGDCOST to provide a more user-friendly spreadsheet interface that will expedite and simplify the inputting process.

All cost evaluations are performed within the framework of EPRI's *Technical Assessment Guide* (P-6587-L), which was updated in September 1989. For the more conventional systems, capital cost estimates are considered to be detailed (Class III); for the less-developed systems, preliminary (Class II). Overall, the estimates are considered to have an absolute accuracy of ±20% and a relative accuracy of ±10%. The accuracy and consistency provided by FGDCOST can help utilities differentiate between candidate processes and alternative configurations.

Some industry forecasts project another 40,000 MW of FGD retrofits in response to Phase 2 of the CAAA. It would be prudent to proceed with Phase 2 planning and cost studies now to explore all available options and determine their cost implications. Extensive preliminary planning and early evaluation of the risks associated with alternative compliance strategies will yield a more comprehensive and cost-effective plan capable of withstanding outside scrutiny.

New Contracts

Project	Funding / Duration	Contractor / EPRI Project Manager
Customer Systems		
Residential Ventilation Controller Technology (RP2417-20)	$104,100 12 months	Geomet Technologies / *J. Kesselring*
Infiltration and Mechanical Ventilation in Low-Rise Multifamily Dwellings (RP2417-21)	$104,300 10 months	Ecotope / *J. Kesselring*
Utility Communications Implementation Utilizing Manufacturing Messaging Technical Support (RP2568-25)	$123,500 24 months	Open Networks Engineering / *L. Carmichael*
Nonazeotropic Water-Cooled Chiller (RP2983-21)	$532,200 12 months	Trane Co. / *P. Joyner*
Slinky/Spiral Ground Coil Development (RP3024-21)	$153,500 23 months	Oklahoma State University / *P. Joyner*
Brushless Doubly Fed Machine System Development Program, Phase 3 (RP3087-19)	$359,800 12 months	Oregon State University / *B. Banerjee*
Evaluation of Electric Utility Demand-Side Management Programs (RP3269-11)	$150,000 22 months	Martin Marietta Energy Systems / *P. Hanser*
High-Efficiency Heat-Pipe-Assisted Supermarket Dehumidification System Data Collection System and Monitoring (RP3280-[illegible])	$107,500 24 months	D. W. Abrams, P.E. & Associates / *M. Khattar*
Computer-Aided Lighting Design (RP3367-4)	$481,100 12 months	Hart, McMurphy & Parks / *K. Johnson*
Industrial Demand-Side Management Efficiency Program: Process Industries (RP337[illegible]-3)	$450,000 11 months	Chem Systems / *R. Jeffress*
Electrical Systems		
Operator Training Simulator: Conversion to VMS (RP1915-11)	$300,000 28 months	ABB Systems Control Company / *G. Cauley*
Graphic User Interface for Power Flow (RP2746-3)	$508,000 17 months	Bonneville Power Administration / *N. Balu*
Deterioration of Extruded Semiconductive Insulation Shields (RP28[illegible]9-3)	$89,600 21 months	Utility Equipment T&D / *B. Bernstein*
Development of Advanced Composite Materials for Utility Applications (RP3229-1)	$249,500 21 months	Foster-Miller / *T. Kendrew*
Development of a Superconducting Transmission Cable System (RP7911-24)	$180,000 10 months	Pirelli Cable Corp. / *D. Von Dollen*
Environment		
Nondestructive Testing of Synthetic Liners (RP1457-11)	$128,600 10 months	I-Corp International / *M. McLearn*
Effects of Low-Sulfur Coal Firing on Cyclone Thermal Performance (RP1835-2[illegible])	$96,800 26 months	Central Illinois Public Service Co. / *A. Kokkinos*
Wastewater Treatment Technologies for Power Plant Water Management: Scoping Study (RP2114-11)	$192,000 12 months	Sargent & Lundy Engineers / *B. Nott*
Speciation of Arsenic, Chromium, and Nickel in Fly Ash, and Metabolic Toxicity Study (RP2485-27)	$138,700 23 months	University of Louisville / *L. Goldstein*
Full-Scale Evaluation of Retrofit Low-NO_x Burners at Homer City 2 (RP2916-19)	$610,700 18 months	Radian Corp. / *D. Eskinazi*
Role of Trust in Risk Perception and Risk Management (RP2955-8)	$150,000 26 months	Decision Science Research Institute / *A. Thrall*
Effects of Magnetic Field Exposure on Human Melatonin (RP2964-15)	$107,400 5 months	Midwest Research Institute / *R. Black*

Project	Funding / Duration	Contractor / EPRI Project Manager
Cellular Responses to Low-Frequency Electric and Magnetic Fields: Calcium Fluctuations and Channel Function in Osteoblast Cells (RP2965-21)	$446,100 36 months	SUNY Research Foundation / *C. Rafferty*
Acidic Aerosols Exposure Assessment (RP3237-1)	$600,000 29 months	Environ Corp. / *L. Levin*
Utilization of Coal Combustion By-products in Agriculture and Land Reclamation: Market Analysis for Midwest Region (RP3270-3)	$69,200 12 months	Geotechnology / *M. Elrashidi*
Exploratory & Applied Research		
Thin-Film Technology for Solid Oxide Fuel Cells (RP2426-55)	$300,000 23 months	Gas Research Institute / *W. Bakker*
CeO_2 Electrolyte for Solid Oxide Fuel Cell Applications (RP2426-58)	$311,900 36 months	Ceramatec / *W. Bakker*
Fuels and Chemicals From Synthesis Gas: Status, Direction, Potential (RP8003-33)	$75,000 10 months	University of Pittsburgh / *N. Stewart*
Integrated Sensors: Industry-University Research Center (RP8004-17)	$100,000 24 months	University of California, Berkeley / *J. Maulbetsch*
Fundamental Studies of NO_x Destruction in Diffusion Flames (RP8005-16)	$292,000 35 months	University of Arizona / *A. Kokkinos*
Particle Dispersion in Three-Dimensional Free Shear Flows (RP8006-23)	$133,100 41 months	University of Southern California / *J. Maulbetsch*
Application of Distributed Computing and Data Management Techniques to Simulation and Control of Complex Systems (RP8010-26)	$283,500 35 months	Rutgers University / *A. Wildberger*
Fractal Indicators of Ecological Responses to Climate Change (RP8011-15)	$112,500 34 months	University of New Mexico / *L. Pitelka*
Models of the Biological Cycle of Carbon in the Ocean (RP8011-17)	$135,300 17 months	Princeton University / *R. Goldstein*
Electrically Driven Nonequilibrium Fusion: Analytical, Phenomenological, and Performance Studies (RP8012-1[illegible])	$149,900 11 months	Energy/Matter Conversion Corp. / *R. Hirsch*
Steam Chemistry and Corrosion in Steam Turbines (RP9002-1)	$96,800 9 months	Stress Technology / *B. Dooley*
Generation & Storage		
Ramp Excursion Method for Fossil Plant Cycling Commitment Decisions (RP1[illegible]84-37)	$55,200 11 months	Applied Analytics Associates / *D. O'Connor*
Application of Neural Networks for Vibration Signature Analysis (RP1864-11)	$[illegible]8,500 [illegible] months	Karta Technology / *R. Colsher*
Dynamic Simulation Model of Highly Integrated Entrained-Flow Gasification–Combined-Cycle Power Plant (RP2524-16)	$110,800 19 months	David S. Weber / *N. Hertz*
Cool Water Simulator Upgrade (RP2524-18)	$[illegible]8,400 4 months	David S. Weber / *J. McDaniel*
Advanced Deposition and Substrate Technologies for Silicon-Film Photovoltaics (RP2611-5)	$299,900 12 months	Martin Marietta Energy Systems / *F. Goodman*
Turbomachinery for IGCASH (Integrated Gasification–Compressed-Air Storage With Humidification) and CASH Cycle Applications (RP2620-10)	$96,500 30 months	Energy Storage & Power Consultants / *A. Cohn*
Expert System for Auxiliary Equipment Monitoring and Diagnosis (RP2626-4)	$177,100 12 months	Expert Systems Consulting Group / *J. Stein*
Turbine Efficiency Improvement (RP2818-7)	$286,900 10 months	Stress Technology / *R. Leyse*

Project	Funding/ Duration	Contractor/EPRI Project Manager
Generation & Storage (cont.)		
Diesel Generator NO_x Control Performance Enhancement (RP2832-11)	$520,600 29 months	Hawaiian Electric Co./ *H. Schreiber*
Utility Benefits of Superconducting Magnetic Energy Storage (RP3116-3)	$50,000 11 months	Bonneville Power Administration/*S. Chapel*
Value of Energy Storage: Screening Analysis and Tools (RP3116-4)	$83,200 10 months	Decision Focus/*S. Chapel*
Nitrous Oxide Bench-Scale Studies (RP3197-11)	$74,800 9 months	Ahlstrom Pyropower/ *R. Brown*
Prototype Development of a Rotor-Mounted Scanner for Turbine-Driven Generators (RP3205-1)	$1,024,700 20 months	STI Optronics/*J. Stein*
State-of-the-Art Power Plant (RP3222-1)	$2,543,300 45 months	Sargent & Lundy Engineers/*S. Pace*
Humid-Air-Turbine Cycle: Technical Services Assistance (RP3251-6)	$145,000 28 months	Energy Storage & Power Consultants/*A. Cohn*
2-MW MCFC Plant Reliability and Availability Analysis and Fuel Cell Module Design (RP3252-3)	$443,200 6 months	Fuel Cell Engineering Corp./*E. Gillis*
High-Concentration Photovoltaic Integrated Array: Design, Development, and Deployment (RP3256-4)	$250,400 24 months	Scientific Analysis/ *F. Dostalek*
Air-Permitting-Strategy Guidance for Compressed-Air Energy Storage Plants (RP3268-3)	$50,700 11 months	Radian Corp./*B. Mehta*
Strategic Analysis of Biomass and Waste Fuels for Electric Power Generation (RP3295-2)	$500,000 15 months	Appel Consultants/ *C. McGowin*
Wood Ash and Wood Energy Production (RP3295-3)	$164,400 36 months	SUNY Research Foundation/*E. Hughes*
Field Tests of Whole-Tree Energy Technology (RP3295-4)	$517,800 9 months	Energy Performance Systems/*E. Hughes*
Renewable Fuels Perspectives Document (RP3295-6)	$145,000 6 months	Pacific Gas and Electric Co./*E. Hughes*
Integrated Energy Systems		
Integrated EMF Risk Management (RP2560-3)	$379,900 14 months	University of Southern California/*G. Hester*
Framework for Assessing Market Management Benefits of Market-Based Generation (RP2801-6)	$50,000 12 months	Mohamed El-Gasseir/ *R. Siddiqi*
Short-Term Reliability Planning and Implementation System (RP3145-3)	$140,000 11 months	Applied Decision Analysis/*R. Siddiqi*
Effect of Overhaul on Equipment Availability (RP3360-2)	$50,000 24 months	ARINC Research Corp./ *J. Weiss*
Nuclear Power		
Transient Fuel Behavior Analysis With FREY Code (RP1117-5)	$125,000 10 months	Anatech Research Corp./ *L. Agee*
Improved Soil Spring Method (RP1444-19)	$50,600 2 months	Bechtel Group/*H. Tang*
Validation of RETRAN-03 for Natural Circulation (RP2291-3)	$100,000 12 months	Computer Simulation and Analysis/*L. Agee*
Maintenance Guide for ABB Medium-Voltage Circuit Breakers (RP2814-67)	$102,400 9 months	Grove Engineering/ *J. Sharkey*
Monitoring Corrosion and Biofilm Formation in Power Plants (RP2939-11)	$78,400 28 months	Structural Integrity Associates/*D. Cubicciotti*
License Renewal Application Documents (RP3075-5)	$149,900 13 months	Multiple Dynamics Corp./ *J. Carey*
Development of Decision Aid for Main Coolant Pump Seal Replacement (RP3111-6)	$499,900 24 months	Anacapa Sciences/ *J. Yasutake*
PWR Shutdown Risk Assessment and Management Guidelines (RP3114-68)	$601,800 21 months	Westinghouse Electric Corp./*P. Kalra*
Reliability-Centered Maintenance Workstation (RP3134-2)	$166,200 11 months	Halliburton NUS Environmental Corp./*R. Colley*
On-line Probe for Iron Corrosion Particulates (RP3173-3)	$306,600 25 months	Babcock & Wilcox Co./ *T. Passell*
Advanced Light Water Reactor: First-of-a-Kind Engineering (RP3301-1)	$50,000,000 55 months	Advanced Reactor Corp./ *J. Santucci*
Development of Guidelines for Determining Site-Specific Ground Motion Integration and Analysis Efforts (RP3302-9)	$271,800 15 months	Risk Engineering/ *J. Schneider*
Development of Ground Motion Methodology and Guidelines Using BLWN Model (RP3302-10)	$393,100 15 months	Pacific Engineering & Analysis/*J. Schneider*
Assessment of Ground Motion From Empirical Data (RP3302-12)	$69,000 15 months	Geomatrix Consultants/ *J. Schneider*
Site Effects Guideline for and Site Exploration of Lotung, Taiwan (RP3302-13)	$112,700 15 months	CH2M Hill/*J. Schneider*
Coordination of Drilling and Site Investigations at Gilroy 2 (RP3302-15)	$76,500 6 months	Woodward-Clyde Consultants/*J. Schneider*
Engineering Support for Early-Site-Permit Demonstration Program (RP3302-17)	$198,400 15 months	S. Levy/*S. Gray*
Full-System Decontamination Enhancement Study (RP3307-3)	$257,100 3 months	Pacific Nuclear Systems/ *C. Wood*
Risk-Based Equipment Maintenance Effectiveness Evaluation (RP3323-1)	$470,100 19 months	Halliburton NUS Environmental Corp./ *B. Chu*
Optimization of Safety/Reliability-Based Outage Planning (RP3323-2)	$90,300 6 months	Science Applications International Corp./*B. Chu*
Browns Ferry Instrumentation and Control Upgrade Plan (RP3332-1)	$149,600 10 months	Mollerus Engineering Corp./*R. Torok*
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Outage Reliability and Risk Initiative Planning (RP3333-5)	$67,600 12 months	Quadrex Energy Services Corp./*R. Oehlberg*
Non-Full-Power Data Compilation and Analysis (RP3333-8)	$144,500 13 months	Tenera LP/*B. Chu*
EOPTS Integration on the Browns Ferry Simulator Integrated Computer System (RP3336-1)	$399,200 16 months	Science Applications International Corp./ *W. Reuland*
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Contractors: Regional Economic Research, Inc.; Resource Dynamics Corp.
EPRI Project Manager: P. Hummel

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TR-100176 Final Report (RP2782-4); $200
Contractors: South Dakota State University; National Food and Energy Council
EPRI Project Managers: A. Amarnath, O. Zimmerman

Targeting DSM for Transmission and Distribution Benefits: A Case Study of PG&E's Delta District
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EPRI Project Manager: J. Kesselring

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Contractor: Charles River Associates
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Electric Vehicle Battery Testing and Development at Argonne National Laboratory: 1990 Annual Report
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Contractor: National Research Council of Canada
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EPRI Project Manager: M. Rabinowitz

Proceedings: 1991 EPRI PCB Seminar
TR-100503 Proceedings; $200
EPRI Project Managers: G. Addis, M. McLearn, T. Thrall

TRELSS: A Computer Program for Transmission Reliability Evaluation of Large-Scale Systems, Vols. 1–5
TR-100566 Final Report (RP3159-1); Vol. 1, $200
TR-100566 Computer Manual; Vol. 2, $200
Vols. 3–5, license required
Contractors: Public Service Electric & Gas Co.; Southern Company Services, Inc.; Georgia Institute of Technology
EPRI Project Manager: M. Lauby

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EPRI Project Manager: F. Garcia

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EPRI Project Manager: G. Addis

ENVIRONMENT

Clean Air Act Response: Continuous Emissions Monitoring Workshop
TR-100510 Proceedings (RP1961); $500
EPRI Project Managers: R. Rinsol, C. Dene

Utilization of Coal Combustion By-products for Masonry Construction
TR-100707 Topical Report (RP3176-1); $200
Contractor: University of Wisconsin, Milwaukee
EPRI Project Manager: D. Golden

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TR-100751 Interim Report (RP2485-3); $200
Contractor: Battelle, Pacific Northwest Laboratories
EPRI Project Manager: M. Elrashidi

Supercritical Fluid Extraction for the Analysis of Contaminated Soils
TR-100754 Final Report (RP2879-4); $200
Contractor: Battelle, Pacific Northwest Laboratories
EPRI Project Manager: I. Murarka

EXPLORATORY & APPLIED RESEARCH

Calcium Carbonate Impregnation of Coal
TR-100570 Final Report (RP8003-18); license required
Contractor: Jet Propulsion Laboratory, California Institute of Technology
EPRI Project Manager: C. Kulik

GENERATION & STORAGE

Shell Coal Gasification Project: Gasification of Eleven Diverse Feeds
GS-7531 Interim Report (RP2695-1); $200
Contractor: Shell Development Co.
EPRI Project Manager: N. Stewart

Comparison of Advanced Steam Temperature Control Algorithms for Fossil-Fuel-Fired Utility Power Plants
TR-100342 Final Report (RP2710-13); $200
Contractor: Honeywell, Inc.
EPRI Project Managers: M. Divakaruni, J. Weiss

Zero-Discharge Wastewater Treatment Facility for a 900-MWe GCC Power Plant
TR-100375 Final Report (RP2221-25); $200
Contractor: CH2M Hill
EPRI Project Manager: M. Epstein

Cost and Quality Management: Making Fossil Power Plants More Competitive—Phase 1
TR-100377 Final Report (RP2989-5); $550
Contractor: Center for Productivity and Manufacturing Engineering, San Jose State University
EPRI Project Manager: R. Frischmuth

Proceedings: 1991 EPRI Gas Turbine Procurement Seminar
TR-100540 Proceedings (RP2915-6); $200
Contractor: Carnot
EPRI Project Manager: H. Schreiber

Coal Desulfurization by Perchloroethylene Processing, Vols. 1–3
TR-100551 Final Report (RP3027-1); $200 each volume
Contractor: Midwest Ore Processing Co., Inc.
EPRI Project Manager: C. Kulik

Proceedings: Sixteenth Annual EPRI Conference on Fuel Science
TR-100632 Proceedings (RP832-99); $200
EPRI Project Managers: N. Stewart, H. Lebowitz

Molten Carbonate Fuel Cells as Distributed-Generation Resources: Case Studies for the Los Angeles Department of Water and Power
TR-100686 Final Report (RP1677-20); $200
Contractor: Mohamed M. El-Gasseir
EPRI Project Managers: D. Rastler, R. Siddiqui

Proceedings: 1991 Fuel Oil Utilization Workshop
TR-100701 Proceedings (RP2778-8); $200
Contractor: Carnot
EPRI Project Manager: W. Rovesti

Assessment of Wind Power Station Performance and Reliability
TR-100705 Final Report (RP1590-10); $200
Contractor: R. Lynette & Associates, Inc.
EPRI Project Manager: J. Berning

Evaluation of the Westinghouse Solid Oxide Fuel Cell Technology for Electric Utility Applications in Japan
TR-100713 Final Report (RP1676-13); $200
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: D. Rastler

INTEGRATED ENERGY SYSTEMS

Engineering and Economic Evaluation of Pressurized Fluidized-Bed Power Plants
IE/GS-7342 Final Report (RP3167-1); $500
Contractor: Bechtel Group, Inc.
EPRI Project Manager: G. Booras

NUCLEAR POWER

Determination of Thermodynamic Data for Modeling Corrosion, Vol. 4: Chloride Ion Interaction With Magnesium, Calcium, and Hydrogen Ions at 250–325°C
NP-5708 Final Report (RPS407-01); $200
Contractor: Brigham Young University
EPRI Project Managers: P. Paine, P. Millett

TMI-2 Postaccident Data Acquisition and Analysis Experience
NP-7156 Interim Report (RP2558-2); $200
Contractor: Grove Engineering, Inc.
EPRI Project Manager: R. Lambert

Guideline for the Utilization of Sampling Plans for Commercial-Grade Item Acceptance (NCIG-19)
NP-7218 Final Report (RPQ101-7); $200
Contractor: Gilbert/Commonwealth, Inc.
EPRI Project Manager: W. Bilanin

Solenoid Valve Maintenance and Application Guide
NP-7414 Final Report (RP2814-36); $9500
Contractor: Strategic Technology and Resources, Inc.
EPRI Project Manager: V. Varma

An Approach to the Analysis of Operator Actions in Probabilistic Risk Assessment
TR-100259 Final Report (RP2847-1; RP2286-2, -3); license required
Contractors: Halliburton NUS Environmental Corp.; Accident Prevention Group; General Physics Corp.
EPRI Project Manager: A. Singh

Reliability Centered Maintenance (RCM) Technical Handbook, Vols. 1 and 2
TR-100320 Final Report (RP2970); license required
Contractor: Halliburton NUS Environmental Corp.
EPRI Project Manager: D. Worledge

Nuclear Power Plant Resource Book, Vols. 1 and 2
TR-100359 Special Report; $20,000 each volume
EPRI Project Manager: S. Green

Proceedings: Seventh International RETRAN Conference
TR-100361 Proceedings; $200
EPRI Project Manager: L. Agee

Optical Fibers in Radiation Environments
TR-100367 Final Report (RP2614-69); $200
Contractor: Ohio State University
EPRI Project Manager: J. Weiss

Individual Plant Examination Review Guide
TR-100369 Final Report (RP3000-46); $200
Contractor: Erin Engineering and Research, Inc.
EPRI Project Manager: J. Sursock

Fire-Induced Vulnerability Evaluation (FIVE)
TR-100370 Final Report (RP3000-41); $50,000
Contractor: Professional Loss Control, Inc.
EPRI Project Manager: J. Sursock

Nuclear Plant Reliability: Data Collection and Usage Guide
TR-100381 Interim Report (RP3200-1); $200
Contractor: Halliburton NUS Environmental Corp.
EPRI Project Manager: B. Chu

PWR Steam Generator Tube Repair Limits: Technical Support Document for Outside Diameter Stress Corrosion Cracking at Tube Support Plates
TR-100407 Final Report (RPS404-15, -19, -21, -24, -29, -30, -31, -32, -33, -36, -37, -70, -71, -72); license required
EPRI Project Manager: L. Williams

Corrosion of Zircaloy-Clad Fuel Rods in High-Temperature PWRs: Measurement of Waterside Corrosion in North Anna Unit 1
TR-100408, Tier 1, Interim Report (RP2757-1); $200
TR-100408, Tier 2, Interim Report; license required
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: O. Ozer

Ground-Motion Attenuation and Earthquake Source Scaling in Eastern North America
TR-100409, Tier 1, Final Report (RP2556-6); $200
TR-100409, Tier 2, Final Report; license required
Contractor: Woodward-Clyde Consultants
EPRI Project Manager: J. Schneider

Foam Rubber Modeling of Seismic Site Effects and Soil-Structure Interaction
TR-100430, Tier 1, Final Report (RP2556-2, -47); $200
TR-100430, Tier 2, Final Report; license required
Contractors: University of California, San Diego; University of Nevada, Reno
EPRI Project Manager: J. Schneider

Spatial Variation of Earthquake Ground Motion for Application to Soil-Structure Interaction
TR-100463, Tier 1, Final Report (RP2978-1); $200
TR-100463, Tier 2, Final Report; license required
Contractor: Bechtel Civil, Inc.
EPRI Project Manager: J. Schneider

Utility Implementation of EPRI Rod Ejection Accident Methodology
TR-100520 Final Report (RP2941-3); $200
Contractors: Leaders in Management, Inc.; Duke Power Co.
EPRI Project Manager: L. Agee

Steam Line Break Analysis Methodologies: Simulation of PWR Steam Line Break Accidents, EPRI-Sponsored Projects
TR-100521 Final Report (RP2941-1, -2); $200
Contractors: S. Levy, Inc.; Cermak Fletcher Associates, Inc.
EPRI Project Manager: L. Agee

NDE of PWR Fuel: Identifying Candidates for Hot Cell Examination
TR-100543 Interim Report (RP2229-8); $20,000
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: H. Ocken

Irradiation Effects on Grain Boundary Chemistry of Austenitic Stainless Steels
TR-100548 Final Report (RP2680-9); $200
Contractor: Battelle, Pacific Northwest Laboratories
EPRI Project Manager: J. Nelson

Control Room Alarm System Upgrades
TR-100584 Final Report (RP3136-1); license required
Contractor: MPR Associates, Inc.
EPRI Project Manager: J. Ketchel

Cluster-Impact Fusion
TR-100642 Final Report (RP3500-5); $200
Contractor: Purdue University
EPRI Project Manager: M. Rabinowitz

Residual Stress Analysis in BWR Pressure Vessel Attachments
TR-100651 Final Report (RPC102-3); $5000
Contractor: Southwest Research Institute
EPRI Project Manager: M. Behravesh

Fuel Reliability Improvement Guidelines
TR-100659 Final Report (RP2229); license required
EPRI Project Manager: R. Yang

EPRI Events

NOVEMBER

8–11
Wood Pole Conference
Starkville, Mississippi
Contact: Harry Ng, (415) 855-2973

9–11
Substation Diagnostics
Palo Alto, California
Contact: Joe Porter, (202) 293-7510

9–12
International Conference on Low-Level Waste
Baltimore, Maryland
Contact: Carol Hornibrook, (415) 855-2022

9–13
American Society for Nondestructive Testing Thermography Course (Level 1)
Eddystone, Pennsylvania
Contact: John Niemkiewicz, (215) 595-8871

9–13
NDE Training Course: Nuclear Utility Procurement
Charlotte, North Carolina
Contact: Annette Medlin, (704) 547-6110

10–12
PEAC Training Course on Power Quality
Knoxville, Tennessee
Contact: Marek Samotyj, (415) 855-2980

11–12
MIDAS Users Group Meeting
Columbus, Ohio
Contact: Lew Rubin, (415) 855-2743

11–12
NSAC–Operational Reactor Safety Engineering and Review Group Workshop
New Orleans, Louisiana
Contact: Linda Nelson, (415) 855-2127

12–13
Underground T&D Construction Workshop
St. Petersburg, Florida
Contact: Tom Rodenbaugh, (415) 855-2306

16–19
Decision Analysis for Utility Planning
Miami, Florida
Contact: Charles Clark, (415) 855-2994

16–19
NDE In-service Inspection Training Course: Weld Overlays
Charlotte, North Carolina
Contact: Annette Medlin, (704) 547-6110

17–19
AIRPOL '92 International Seminar: Solving Corrosion Problems in Air Pollution Control Equipment
Orlando, Florida
Contact: Paul Radcliffe, (415) 855-2720

17–19
Heat Rate Improvement Conference
Birmingham, Alabama
Contact: Pam Turner, (415) 855-2010

17–19
ROBAL Computer Code for Rotating-Machinery Balancing
Eddystone, Pennsylvania
Contact: Tom McCloskey, (415) 855-2655

17–20
NDE Training Course: Microbiologically Influenced Corrosion
Charlotte, North Carolina
Contact: Annette Medlin, (704) 547-6110

18–20
EPRI-EUMRC Market Research Symposium
Dallas, Texas
Contact: Susan Bisetti, (415) 855-7919

18–20
1992 PWR Plant Chemists' Meeting
San Diego, California
Contact: Peter Paine, (415) 855-2076

30–December 4
NDE Technical Skills Training Course: Ultrasonic Examination (Level 3)
Charlotte, North Carolina
Contact: Annette Medlin, (704) 547-6110

DECEMBER

2–4
Noncombustion Waste Seminar
Orlando, Florida
Contact: Susan Bisetti, (415) 855-7919

7–11
NDE Technical Skills Training Course: Basic/Specific (Level 3)
Charlotte, North Carolina
Contact: Annette Medlin, (704) 547-6110

7–16
NDE In-service Inspection Training Course: IGSCC Detection
Charlotte, North Carolina
Contact: Annette Medlin, (704) 547-6110

8–9
Space Charge in Extruded Cables
Scottsdale, Arizona
Contact: Bruce Bernstein, (202) 293-7511

8–11
Machinery Alignment Course
Eddystone, Pennsylvania
Contact: John Niemkiewicz, (215) 595-8871

9–11
1992 Advanced Computer Technology Conference
Scottsdale, Arizona
Contact: Pam Turner, (415) 855-2010

14–18
NDE Technical SkillsTraining Course: Visual Examination (Level 3)
Charlotte, North Carolina
Contact: Annette Medlin, (704) 547-6110

15–18
Motor Monitoring and Diagnostics Course
Eddystone, Pennsylvania
Contact: John Niemkiewicz, (215) 595-8871

FEBRUARY 1993

3–5
Coal-Handling Systems: State of the Future (call for papers)
Pensacola, Florida
Contact: Barbara Arnold, (412) 479-6012

9–10
Conference on Energy-Efficient Electric Motor Systems
Baltimore, Maryland
Contact: Les Harry, (415) 855-2558

9–11
Conference on Cable Condition Monitoring
San Francisco, California
Contact: Linda Nelson, (415) 855-2127

10–12
Workshop on Air-Operated Valves
Salt Lake City, Utah
Contact: Ken Barry, (704) 547-6040

17–19
New Equipment and Services for Commercial Foodservice Customers
New Orleans, Louisiana
Contact: Susan Bisetti, (415) 855-7919

MARCH

1–3
International Symposium on Improved Technology for Fossil Power Plants: New and Retrofit Applications
Washington, D.C.
Contact: Lori Adams, (415) 855-8763

24–26
6th National Demand-Side Management Conference
Miami Beach, Florida
Contact: Pam Turner, (415) 855-2010

APRIL

5–8
10th Particulate Control Symposium
Washington, D.C.
Contact: Lori Adams, (415) 855-8763

13–14
Generator and Large-Motor Winding Assessment Using MICAA
Philadelphia, Pennsylvania
Contact: Jan Stein, (415) 855-2390

Contributors


Schneider


Von Dollen


Wyzga


Damsky


Iveson

Superconductors Are Still Hot (page 4) was written by Taylor Moore, *Journal* senior feature writer, with assistance from two EPRI research managers.

Thomas Schneider, executive scientist, comanages the Office of Exploratory & Applied Research, directing programs in physical and mathematical sciences. He coordinates the Institute's research projects and relationships with other organizations in high-temperature superconductivity. Schneider joined EPRI in 1977 after four years as a research physicist with Public Service Electric & Gas in New Jersey. From 1985 to 1987, he served as president of the nonprofit Lighting Research Institute. Schneider earned a BS degree from Stevens Institute of Technology and a PhD in physics from the University of Pennsylvania.

Donald Von Dollen is a project manager for superconductivity in the Electrical Systems Division. He joined EPRI in 1991 after three years as an engineer in the R&D and technical services programs at Pacific Gas and Electric. Von Dollen earned a BS in physics from California State University, Sacramento. ■

Breakthrough in Electrical Burn Treatment (page 16) was written by John Douglas, science writer, with technical information from **Ronald Wyzga** of EPRI's Environment Division.

Wyzga has been senior manager of the Health Studies Program since 1988, previously having managed work in health effects and environmental risk assessment. Before coming to EPRI in 1975, he was with the Organization for Economic Cooperation and Development for four years and also served as a professor of statistics at the American College in Paris. Wyzga received an AB in mathematics from Harvard College, an MS in statistics from Florida State University, and an ScD in biostatistics from the Harvard School of Public Health. ■

Preparing for Disaster (page 22) was written by science writer Bob McGee with assistance from two members of the Electrical Systems Division.

Ben Damsky is manager for power electronics systems in EPRI's Transmission Substations Program. Before joining the Institute in 1984, he spent 19 years with General Electric Company, managing engineering projects in a number of areas, including advanced valves for HVDC systems and ultrahigh-power thyristors. Damsky holds a BS degree in physics from Princeton University and an MS in the same field from the University of Pennsylvania.

Robert Iveson, staff technical advisor since 1988, formerly managed the Power System Planning and Operations Program. He came to EPRI in 1980 after 20 years with New York State Electric & Gas, where his work included 9 years as supervisor of transmission planning for the New York Power Pool. Iveson earned BS and MS degrees in electrical engineering from Rensselaer Polytechnic Institute and Syracuse University, respectively. ■

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