Power Applications for Superconductivity

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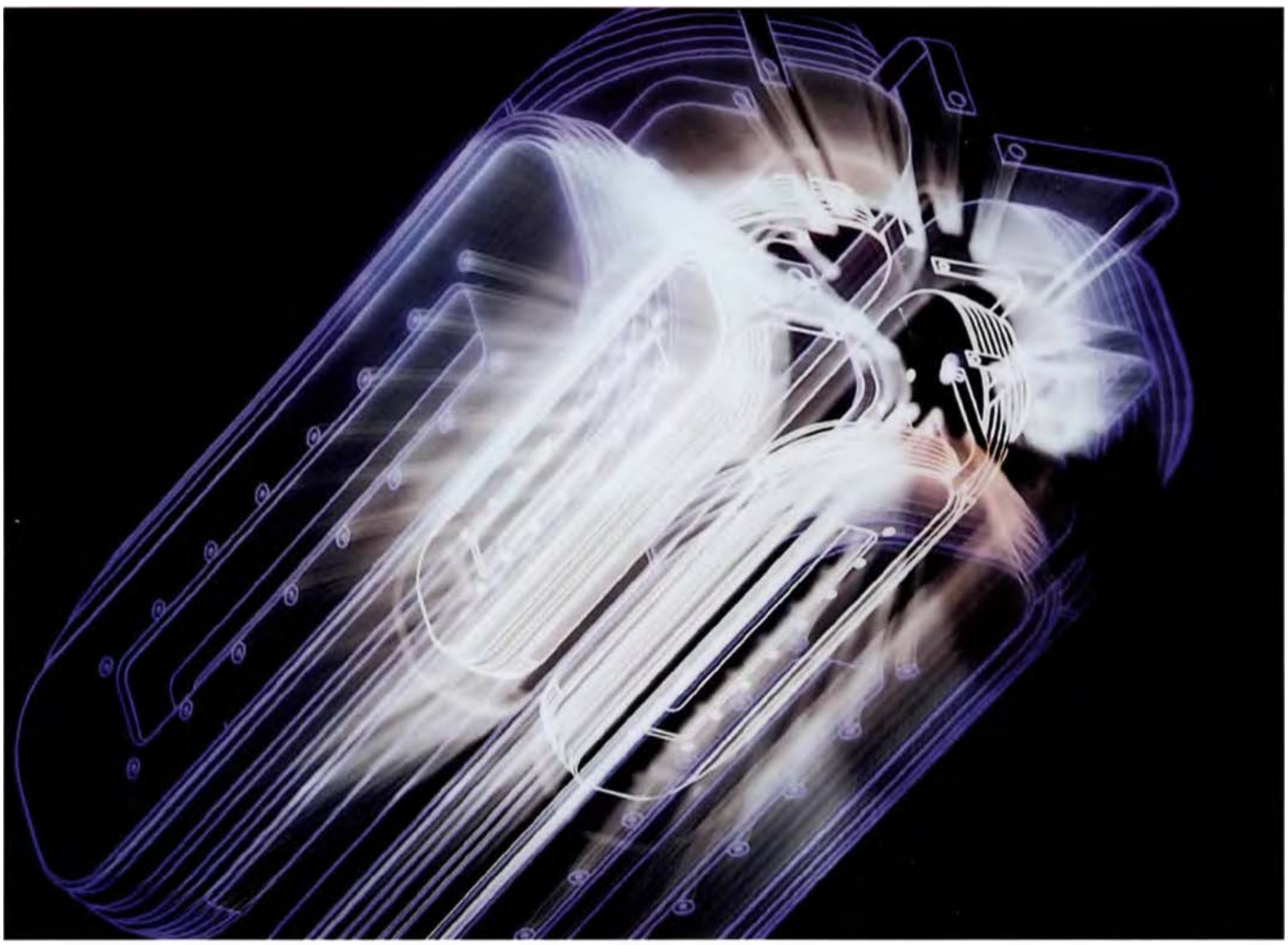
ELECTRIC POWER RESEARCH INSTITUTE

EPRI JOURNAL

JULY/AUGUST 1996



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Cover: Superconducting coils for advanced motors represent just one of the many applications now on the drawing board for high-temperature superconducting wire. (Image courtesy of American Superconductor Corp.)

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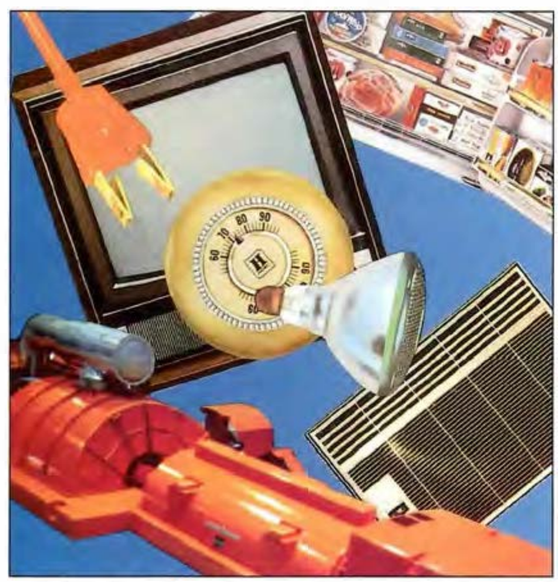

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PRODUCTS

EPRI-sponsored deliverables now available to utilities and their customers

Emission Factors Handbook

In order to meet new permit requirements under Title V of the 1990 Clean Air Act Amendments, electric utilities with fossil-fuel-fired power plants must estimate emissions of hazardous air pollutants from these plants. The extensive sampling procedures required for such estimates are both time-consuming and costly for individual utilities to undertake. That's why EPRI developed the *Emission Factors Handbook* (TR-105611). The emission factors presented in this guide are intended to assist utility personnel in estimating emissions of trace substances ranging from chlorine to mercury. The factors are based on actual field measurements conducted by EPRI and the Department of Energy at 51 representative U.S. power plants.

For more information, contact Paul Chu, (415) 855-2812.
To order, call the EPRI Distribution Center, (510) 934-4212.

Distributed Resources: A Market Assessment

As the business environment of electric utilities becomes more competitive, distributed resources are emerging as a potentially important supplement to the traditional central-station power plant. Ranging from generation technologies like combustion engines and photovoltaic systems to nongeneration resources like demand-side management programs and real-time pricing, distributed resources are modular supply options that can capture location-specific benefits, improve the overall economic efficiency of the supply system, and enhance customer service. In order to plan for the integration of distributed resources into the electricity supply system, utilities need credible information on whether these resources are likely to provide competitive alternatives and, if so, how they might affect other utility products. Such information has been gathered into this report (TR-106055) to help utilities incorporate distributed resources into their strategic business planning and position themselves competitively for future energy markets.

For more information, contact Connie Smyser, (415) 855-2396.
To order, call the EPRI Distribution Center, (510) 934-4212.

On-Line Corrosion Probe

Corrosion problems cost the electricity generation industry billions of dollars annually in maintenance expenses and power lost during forced outages. For this reason, closely monitoring corrosion in fossil fuel and nuclear power plants is critical. Traditional monitoring techniques, which involve retrieving numerous water samples and testing them in a laboratory, are time-consuming and indicate only average corrosion product levels over long sampling intervals. In contrast, the advanced, on-line Corrosion Product Monitoring System, developed by EPRI in collaboration with Babcock & Wilcox and commercialized by DETEX Inc., allows continuous measurement of both particulate and dissolved corrosion products. Sample water flows through a specially designed cell containing a filter that captures corrosion products. X-ray fluorescence spectroscopy is used to measure the deposited material as it accumulates. Analysis of the material is immediate and continuous.

For more information, contact Peter Millett, (415) 855-8510.
To order, call DETEX, (330) 438-0231.

Water Chemistry Software

Determining the optimal water chemistry for preventing corrosion problems in PWR plants is a complex and plant specific task. To help utilities design water chemistry programs that are tailormade for their plants, EPRI developed chemWORKS™. A software package made up of six interactive codes, chemWORKS allows utility personnel to perform the technical and economic evaluations necessary for diagnosing and optimizing PWR water chemistry. (Additional codes now under development address chemistry problems in BWR plants.) Each of the six PWR codes can be used independently:

- **PWR Secondary Chemistry Simulator** Allows in-depth modeling of the water chemistry of PWR secondary systems, including turbine extraction lines, feedwater heaters, drain tanks, and flash tanks.
- **MULTEQ-REDOX** Determines the pH of the concentrated, hightemperature aqueous solutions that form in the crevices of PWR steam generators.
- **CrevSim** Predicts crevice chemistry on a near-real-time basis.
- **Hideout Return Spreadsheet** Quickly calculates the level of impurities that return to the water during power reductions. (Its output can be used to improve the accuracy of CrevSim's predictions.)
- **AminMod** Offers a simplified secondary-system simulation that focuses strictly on the use of volatile species, such as amines and organic acids. A built-in spreadsheet calculates the cost of this corrosion control method.
- **PWR Plant and Chemistry Database** Lists industry contacts with experience in chemistry issues and presents detailed design and operating characteristics of their plants. Users can search the list by name, by issue, or by features of a plant's chemistry program.

For more information, contact Peter Millett, (415) 855-8510.
To order, call GEBCO Engineering Inc., (707) 823-5237.

New President, Executive Appointments Announced

At its April meeting, EPRI's Board of Directors unanimously elected Kurt Yeager as president and chief executive officer, succeeding Richard Balzhiser, who is retiring after eight years as EPRI's top executive. Yeager previously served as executive vice president and chief operating officer.

After joining EPRI in 1974, Yeager held a series of R&D management positions before being named senior vice president of technical operations, responsible for the integrated management of all EPRI technical programs, in 1990. In 1994, he was named senior vice president for strategic development and, in 1995, executive vice president and chief operating officer. Before joining EPRI, Yeager was director of energy R&D planning for the Environmental Protection Agency's Office of Research, and still earlier he was associate head of the Environmental Systems Department at the MITRE Corporation. Yeager earned a BS in chemistry at Kenyon College and completed postgraduate studies in chemistry and physics at Ohio State University and the University of California at Davis. He is also a distinguished graduate of the Air Force Nuclear Research Officers' Program and a fellow of the American Society of Mechanical Engineers.


YEAGER


RUDMAN


BERRY


KUMIN

Richard Rudman was appointed EPRI's chief operating officer by the Board at its August meeting. Rudman previously was EPRI's senior vice president for corporate services. In recommending the new appointment, Yeager said that Rudman's COO role "will be a key asset in confidently building EPRI for the future. My focus will be on developing technical and business strategies, achieving our corporate performance goals, and building EPRI's stakeholder relationships. I will rely on Ric to implement EPRI's business plan, to provide tactical leadership, and to increase member satisfaction with EPRI results. I believe our complementary capabilities in these new roles will ensure the greatest benefit to EPRI and its stakeholders."

Rudman joined EPRI in 1973 as an assistant to the president after working for IBM. At EPRI, he became director of the Policy Planning Division and, in 1981, was named director of the Information Services Group. Rudman served as vice president for industry relations and information services from 1983 to 1986. He rejoined EPRI in 1989 after two years as president and CEO of Aster Publishing and was named a senior vice president in 1990. Rudman earned BS and MS degrees in engineering at the University of California at Los Angeles.

The appointment of William Berry as chief financial officer, responsible for the Institute's financial, fiscal, and contracting policies and programs, was announced in April by Yeager. Berry's "experience both as chief administrative officer at Raychem and in CEO and COO positions with entrepreneurial ventures is just the right combination to ensure that EPRI has leading-edge business systems as we offer members more choices in accessing the technologies they need to prosper in a changing industry," said Yeager.

Before joining EPRI, Berry was CFO at Compression Labs in San Jose, California, and CEO of Optical Shields in Menlo Park, California. Before that, he worked for 21 years in a variety of positions at Raychem in Menlo Park, ultimately as chief administrative officer. Berry earned a BS in industrial engineering and an MBA at Stanford University.

Jane Kumin, EPRI's general counsel, has been appointed to the additional post of corporate secretary. In this position, Kumin is responsible for supporting corporate governance activities, including activities of the Board of Directors and its committees. She succeeds Alex Fremling, who has retired from EPRI.

Before coming to the Institute in 1989, Kumin served as general counsel and corporate secretary at Thermal Power Company; earlier she was regulatory counsel for energy and environmental matters at Natomas Company. From 1978 to 1980, she was a member of the policy staff for the president of the California Public Utilities Commission. Kumin holds BA and MPA degrees from Harvard University and a JD degree from the Boalt Hall School of Law at the University of California at Berkeley.

Membership Offering Provides Flexible Options for Changing Business Needs

EPRI's 1997 membership offering, now in the hands of current and prospective members, significantly extends the Progressive Flexibility program introduced in 1995—providing even greater flexibility in program choice and more options for participation in the Institute's networked, collaborative R&D enterprise. While the 1996 membership offering attracted a record level of participation from U.S. and international utilities, the goal for 1997 is to achieve an even higher level of participation.

About 80 research targets form the foundation of the 1997 offering, representing a portfolio of synergistic projects aligned with EPRI's five business groups: Customer Systems, Environment, Generation, Nuclear Power, and Power Delivery. In addition, six joint targets are being introduced to give member companies the benefit of integrated solutions to complex issues that cross business group boundaries. In 1997, members may continue to support the entire EPRI R&D program or may select any number of targets to shape an R&D commitment that is closely aligned with their business strategies.

The 1997 offering provides several additional options for participation in the EPRI program. Both large and small collaborative groups are possible. Members may fund sponsored research consistent with EPRI's overall research plan in support of their own specific strategic goals. Tailored collaboration, which allows members to direct supplemental funds matched by EPRI dollars toward specific projects, will be offered again. Members also will receive additional rights to intellectual property, which increase with the level of supplemental funding.

EPRI member relations executives and staff are available to answer questions and provide companies with the information they need to make the best possible funding decisions. A special toll-free telephone information service—800-313-EPRI (3774)—will be staffed by EPRI personnel through August. Also, questions about the offering can be faxed to 800-314-EPRI for an answer within 24 hours. An electronic spreadsheet will be available on EPRI's public Internet home page (www.epri.com) to help companies calculate possible funding scenarios.

Powering Progress Through Electronic Communication on the Internet

Members of EPRI's existing on-line community—EPRINET—are beginning the transition to a new electronic environment that incorporates the existing news and information content in a multimedia, Internet-based World Wide Web site offering even greater functionality, services, and resources. This new electronic information source, called EPRIweb, is designed to allow thousands of users to engage in direct, interactive collaboration with EPRI staff and other members of the electricity R&D community. EPRIweb will replace EPRINET by the end of the year as the key electronic gateway through which member utilities can access EPRI information and services.

Approximately 20 member utilities participated in a series of beta tests of EPRIweb that began early this year. Improvements and additional features resulting from their feedback are incorporated in the production release. Accessible only through an EPRI-issued ID and password, EPRIweb joins the Institute's public Internet home page (www.epri.com).

Current users of EPRINET began receiving new EPRIweb IDs and passwords in May. EPRIweb provides nearly all the information available through the text-only, mainframe-based EPRINET system, along with additional capabilities under development, such as on-line software downloading. EPRIweb, built on the Netscape Community web server software running on a Sun SPARC 20 platform, provides secure access to the Institute's research information by allowing users to access information only for the EPRI business units they currently fund. Next year, EPRIweb access will be based on the targets in the 1997 membership offering.

In September, Southern Company Services, a subsidiary of one of the members that beta-tested EPRIweb, will host the 1996 EPRIweb Conference in Atlanta, Georgia. The conference will focus on the product's rollout and implementation strategy, user experiences, and future development directions. *For more information, contact Margaret Gragg, EPRIweb marketing manager, (415) 855-2040.*

AMERICAN SUPERCONDUCTOR CORP.

As a scientific phenomenon, superconductivity has been recognized for 85 years, but its potential for electric power applications that could have a major technological and social impact has broadly captured the interest of electric utilities only in about the past 10 years. Worldwide scientific and media excitement was ignited in 1986 when two physicists at an IBM research laboratory in Switzerland, working with small samples of an obscure class of rare-earth-containing ceramic oxides of copper, reported signs of resistance-free conduction of electric current at the unprecedented high absolute temperature of 35 Kelvin. Before that, the search for higher-temperature superconducting materials had gone slowly: the known transition temperature to a superconducting state had taken 75 years to increase from the 4 K boiling point of liquid helium (the transition temperature of the first metals in which the phenomenon was observed) to around 23 K.

Within a year of the 35 K achievement, other scientists reported superconductivity at a transition temperature of 91 K in a sim-

Applications for

Superconductivity

THE STORY IN BRIEF Within only a decade of being discovered, a new class of materials that conduct electricity with virtually no resistance losses are inside working prototypes of some of the key elements of a superconducting power grid. Several prototype devices are being tested or are nearing testing on utility systems. Electric wires that become superconducting when cooled to the affordable operating-temperature realm of liquid nitrogen—as well as coils, magnets, conductors, and machines and power components made with these wires—appear a sure bet to enter commercial markets for utility equipment over the next few years. Whether such high-temperature superconductors capture a significant share of these markets will depend on whether they can deliver a strategic competitive advantage while offering reliability and costs comparable to those of conventional copper or aluminum conductors.

by Taylor Moore

ilar ceramic copper oxide that contained yttrium and barium. Suddenly, practical utility applications of superconductivity appeared to be within reach, because devices made of materials having that transition temperature could operate with cooling by cheap, unexotic liquid nitrogen, which boils at 77 K.

Today materials that become superconducting at transition temperatures as high as 135 K have been verified, and over 100 compounds are considered high-temperature superconductors (HTSs). Successes by scientists around the world during the past decade have led to the commercial development of HTS wires (in kilometer lengths) and devices having, at liquid nitrogen temperature, as much as 100 times the current-carrying capacity of ordinary conductors. Such wires are already being employed to fabricate prototype conductors for use in superconducting underground transmission cables and in device prototypes for other applications.

But for key electric power applications like motors, generators, and magnetic energy storage systems, superconductors must be able to maintain their super performance while saturated by very strong, self-generated magnetic fields. The principal HTS material that has been successfully fabricated into flexible wire for use in R&D and in prototype devices—a bismuth strontium calcium copper oxide (BSCCO) compound—loses its superconductivity in the presence of moderate magnetic fields at 77 K, although it performs quite well when cooled to 20–30 K. Recently, the original 91 K material, one of the earliest HTSs known, has been shown to perform very well in high fields at liquid nitrogen temperature. This has led to renewed hope for the material—yttrium barium copper oxide (YBCO)—whose inherently poor grain alignment had previously made it undesirable as practical wire material.

Research on next-generation, high-field YBCO HTS wire technologies struck pay dirt last year when scientists at the U.S. Department of Energy's Los Alamos National Laboratory obtained more than 1 million amperes of current per square centimeter of superconductor cross section (A/cm^2) at 77 K in short lengths of flexible tape. To make the tape, a low-energy ion beam was used to texture a substrate for a 1-micrometer-thick film of YBCO.

The YBCO tape retained a critical current density of up to 100,000 A/cm^2 (one-tenth of its zero-field current density) at 77 K under parallel magnetic fields as high as 8 teslas—several times the fields typically generated in medical magnetic resonance imaging (MRI) machines that use liquid-helium-cooled low-temperature superconductors (LTSs). The current density of the YBCO tape in a high magnetic field is comparable to the highest density obtained today in zero magnetic field at 77 K with the more readily manufacturable, commercial HTS wire, fabricated by powder-in-tube processing and mechanical forming of a BSCCO compound. And experts say that, in principle, YBCO conductors could be capable of current densities as high as 5–7 million A/cm^2.

Soon after the achievement at Los Alamos, which built on pioneering work in Japan five years ago, EPRI—already supporting work at Stanford University and Lawrence Berkeley National Laboratory—extended its program to include the Los Alamos team. Within a year of that team's report, researchers at Oak Ridge National Laboratory said that they had successfully developed a fabrication method for texturing wire substrate to achieve a high degree of YBCO grain alignment and, in turn, high current density. They have since reported obtaining up to 700,000 A/cm^2 with this approach—a rolling and pressing method.

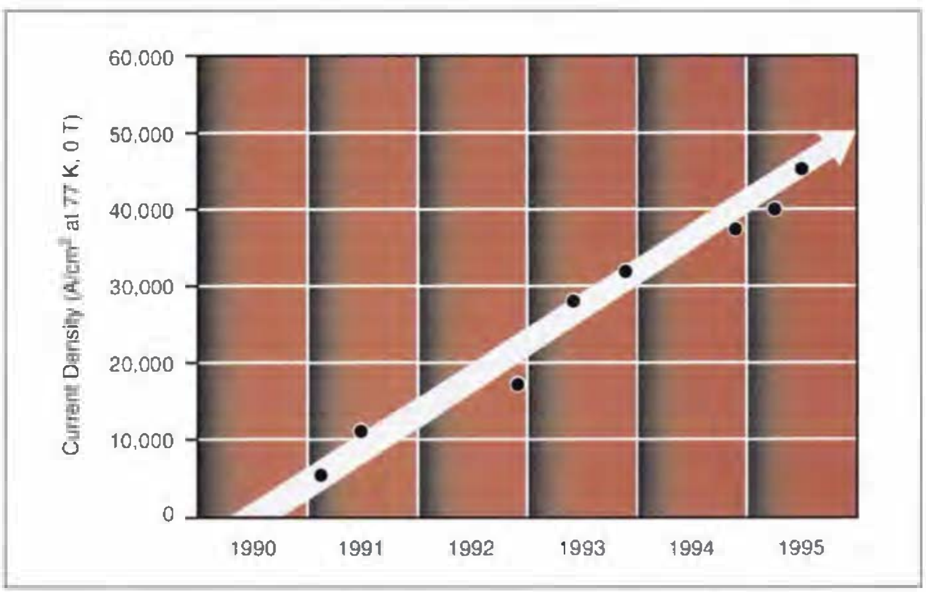
Although success in transferring the excellent performance properties of the YBCO tape from the laboratory to useful lengths of wire produced in a commercial manufacturing environment is by no means assured (see sidebar), the Los Alamos and Oak Ridge achievements with YBCO conductors have invigorated the HTS R&D community, rekindling the excitement that originated with BSCCO wire technology.

Meanwhile, the handful of companies in the United States and abroad that are commercially producing multifilament BSCCO wire continue to increase critical current density, which is nearing 50,000 A/cm^2 at 77 K. Such a level is adequate for practical application because the fill factor (the fraction of superconductor to metal) in such wires is significantly higher than in the thin-film processes used to make YBCO conductors. The performance properties of long lengths of BSCCO wire are now comparable to those obtained with short, research-grade wires, experts say.

Watershed breakthrough

"It is worth considering the past decade's progress in HTS in light of the experience with low-temperature superconductivity," says Paul Grant, an executive scientist on EPRI's Strategic R&D staff and a former IBM research scientist. "The basic practical LTS wire material used today in some large-scale applications, such as MRI magnets, is niobium-titanium [NbTi]. It took almost 25 years from its discovery to fully understand and optimize that material."

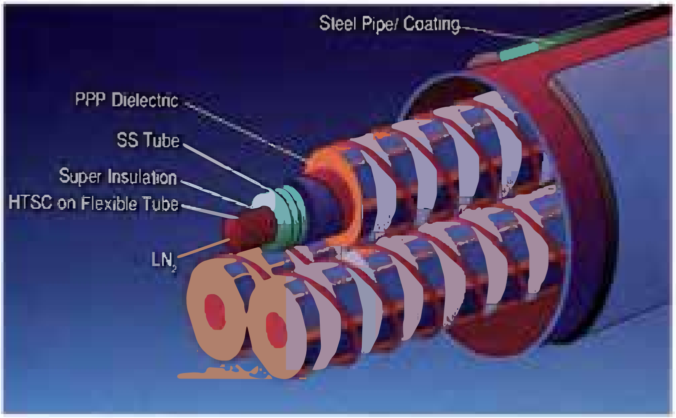
Grant believes that two factors were critical in the rapid progress achieved with the ceramic HTS materials—materials that are intrinsically more difficult to work with than LTSs, which are more like metals. "Unlike the case with low-temperature superconductors, the discovery of high-temperature superconductors was one of those rare scientific breakthroughs that excited people across a wide spectrum of science," says Grant. "Physicists were suddenly thrust into the limelight, but it rapidly extended to engineering, materials science, and much in between. The development of



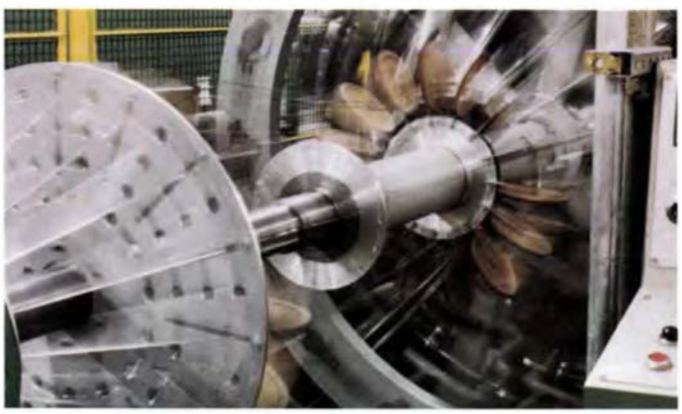
LINEAR CLIMB IN HTS WIRE CURRENT DENSITY Manufacturers continue to raise the current density at liquid nitrogen temperature (and zero magnetic field) in long lengths of commercial multifilament HTS wire based on BSCCO compounds. The progress has been essentially linear during the past five to six years. Data are from American Superconductor Corporation.

GETTING WOUND UP ABOUT HTS POWER CABLES **An effort involving cable manufacturer Pirelli, American Superconductor, EPRI, and DOE's Superconductivity Partnership Initiative is ahead of schedule in developing a prototype HTS transmission cable. Earlier this year, Pirelli modified an industrial cable-winding machine at its South Carolina factory and assembled a 50-meter flexible stranded conductor from several kilometers of multifilament BSCCO wire produced by American Superconductor. The prototype assembly was tested in liquid nitrogen and exceeded the design target with a critical current density of 1800 A dc at 1 μV/cm².**

Prototype stranded conductor



HTS power cable



Cable-winding machine

HTS cable testing in liquid nitrogen

LTS materials was more evolutionary and incremental.

"Equally important in the case of HTS materials was the availability, beginning in the 1970s, of really marvelous analytical instruments like the transmission electron microscope and techniques like Rutherford backscattering," continues Grant. "The new instruments allowed scientists to peer into materials at the atomic scale and to learn the role that each atom plays. That, in turn, led to the development of new processing techniques, first used for semiconductors but now being successfully applied in the equally challenging materials area of HTSs." Grant helped to organize the 10th Anniversary HTS Workshop on Physics, Materials, and Applications—held in Houston last March—at which many of the world's top researchers reported their latest results.

The critical role of wire

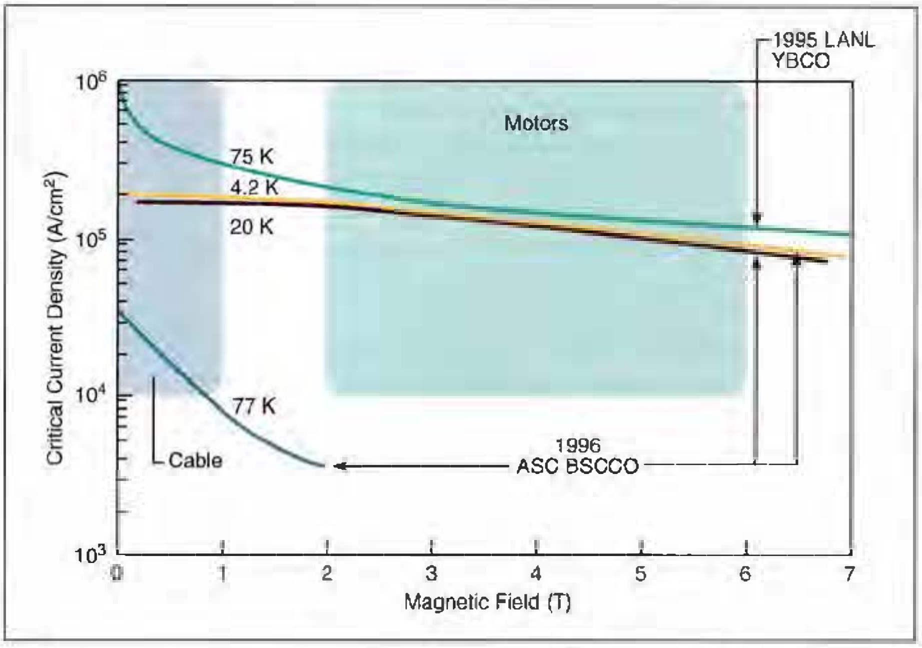
Chip-sized HTS thin films and electronic devices such as signal filters and ultrasensitive magnetic detectors are already at the threshold of commercial use. But virtually every significant electric power application envisioned for HTS technology depends crucially on the development of high-performance multifilament wire. Such wire and stranded conductors fabricated from it must form the coils for motors, the rotor windings for generators, and the conductors for power cables and superconducting magnetic energy storage rings.

According to Grant, EPRI played an important role in catalyzing the early commercialization of HTS wire based on BSCCO compounds. The Institute supported materials research at the University of Wisconsin's Applied Superconductivity Center that helped to identify a lead-stabilized BSCCO compound known as Bi-2223 as one of the most promising candidates. This compound is now the material of choice for wires and tapes produced by the two leading U.S. companies pursuing commercial HTS development: American Superconductor Corporation (ASC) and Intermagnetics General Corporation.

Manufacturers continue to improve the performance of commercial BSCCO wire, which already meets or exceeds the requirements for some power applications, such as conductors for transmission cables. "The key issue in BSCCO is to identify those factors that control the connectivity of the polycrystalline filaments of the wires," says David Larbalestier, professor of materials science and engineering and also physics at the Applied Superconductivity Center. "Continued progress in the critical current densities of the wires has come from careful study of their current-limiting mechanisms," he notes, in particular citing efforts by the Wire Development Group, an association of R&D groups at ASC, Argonne National Laboratory, Los Alamos, the National Institute of Standards and Technology, Oak Ridge, and the University of Wisconsin.

Seemingly inherent limits on the ability of the two-dimensional, polycrystalline structure of BSCCO to pin magnetic flux adequately at high temperatures may mean that it will remain a less-than-ideal HTS wire material for high (>1 tesla) magnetic field applications at liquid nitrogen temperature. Work at Wisconsin and elsewhere has identified many of the critical relationships that limit BSCCO's performance in high magnetic fields at 77 K—relationships between poor flux pinning, low-angle grain alignment, cracks and phase impurities, and the uneven distribution of supercurrent flowing in the material.

Yet as Alex Malozemoff, ASC's chief technical officer, says, "The progress that has been made in the last five years in multifilament BSCCO wire is essentially linear, and there appears to be much potential for further progress. The current densities now being obtained are well within the range of commercial interest. This is, in fact, the wire technology being used in all the application prototypes that are coming together. We are convinced that it will succeed as a first-generation commercial HTS wire."



CRITICAL CURRENT DENSITY IN MAGNETIC FIELDS Commercially available BSCCO-based multifilament wire rapidly loses superconductivity in moderate magnetic fields at the temperature of liquid nitrogen (77 K); it maintains good current density in high fields only when cooled to 20 K or lower. Coated conductors of micrometer-thick YBCO films on a textured substrate, made by scientists at Los Alamos National Laboratory (LANL) using a process called ion-beam-assisted deposition, have shown high current densities in strong magnetic fields at 77 K, albeit in short wire samples in a laboratory. A strategic alliance between EPRI and American Superconductor Corporation (ASC) is pursuing the development of YBCO conductors by means of the ion-beam process and other approaches.

Malozemoff notes that when cooled to 20–30 K, BSCCO wire actually exhibits greater critical current density in high magnetic fields than do commercial LTS materials like NbTi at liquid helium temperature (4 K). While the use of mechanical cryocooling limits the potential HTS economic advantage to some extent, EPRI's Grant believes there could be a near-term market for BSCCO-based high-field magnets operating at low temperatures. Still, experts agree that HTS wire and coils that maintain high current densities in high magnetic fields at 77 K would open a much broader range of application possibilities.

For now at least, the current density and other performance characteristics of commercial BSCCO wire are good enough to keep several application development efforts busy building prototypes, testing them, and refining their designs. These programs provide ongoing feedback to wire manufacturers on how to further improve performance properties. Such efforts provide a glimpse of how HTS materials promise to transform today's electric power grid and to shape the way electricity is managed and used in the future.

Generally, in every potential power application of HTS materials, their much higher current densities and reduced resistive losses will lead to components and systems that are smaller and lighter as well as more powerful and efficient. A superconducting power system will be able to meet growing demand for electricity with fewer power plants and transmission lines than would otherwise be needed.

Virtually all the U.S. development programs for power applications are supported under DOE's Superconductivity Partnership Initiative (SPI), a major government-industry collaborative effort. The participants include several of the national laboratories, various university-based research centers, EPRI, the American HTS wire manufacturers, and other technology companies. Several branches of the defense establishment are also pursuing HTS applications, such as motors, generators, and energy storage.

Underground transmission cables

HTS power cables promise to at least double the capacity of existing underground conduits for a given diameter and voltage. Thus they could provide an important retrofit upgrade option for satisfying demand growth in dense urban areas, and for the longer term, they could make underground transmission a more economical alternative to new overhead lines in nonurban areas. (With today's copper power cables, typically two underground circuits are required to equal the capacity of one overhead line at transmission voltages.)

Underground transmission is perhaps the major HTS application of most-immediate interest to the utility industry, as well as one of the areas showing the most-rapid progress. Although overhead power transmission is much more prevalent, there are currently some 3500 circuit-miles of underground transmission in the United States. And this represents only a fraction of the worldwide market.

Pursuing the Next-Generation HTS Wire

Recent breakthroughs in achieving high critical current densities in significant lengths of tape using the high-temperature superconductor yttrium barium copper oxide (YBCO) have prompted a new strategic alliance between American Superconductor Corporation (ASC) and EPRI. Last March the organizations announced a major initiative to develop and commercialize the next-generation HTS wire for electric power applications. If they can be manufactured on a commercial scale, YBCO-coated HTS conductors are expected to maintain high current densities even in very high magnetic fields, making them useful for numerous applications that depend on high-field magnets.

The ASC-EPRI alliance will collaborate with DOE's Superconductivity Partnership Initiative—particularly with the DOE-funded Los Alamos and Lawrence Berkeley National Laboratories, where recent advances in YBCO thick-film deposition have been made. Additional collaboration is anticipated with academic institutions, corporations, and other government agencies, according to EPRI's Paul Grant.

An initial focus of the alliance will be the significant advances demonstrated at Los Alamos last year in so-called coated-conductor HTS technology, in which thick, highly textured films of YBCO or other material are deposited on flexible tapes. Techniques that are capable of achieving the high degree of grain alignment necessary for high current density and that are also amenable to scale-up have been under investigation by several organizations around the world for the past six years.

The Los Alamos team achieved record levels of current conduction in short samples of tape made by using a process called ion-beam-assisted deposition (IBAD). Flexible substrates of nickel alloy were covered with yttria-stabilized zirconia for coating with YBCO films 1–3 micrometers thick. The Los Alamos technology is an extension of earlier work at Fujikura in Japan, related work at Lawrence Berkeley National Laboratory, and still earlier work on semiconductor applications at IBM's Yorktown Heights, New York, research center.

IBAD is but one of a variety of possible next-generation HTS wire technologies that the ASC-EPRI alliance will explore and evaluate for eventual industrial scale-up. Other approaches to substrate texturization for preferential grain alignment include metallurgical and mechanical techniques—"sometimes called heat 'em and beat 'em methods," notes Grant. Earlier this year, researchers at Oak Ridge National Laboratory demonstrated high current densities in short wire samples produced with a promising approach of this kind—rolling-assisted biaxially textured substrates—with pulsed-laser deposition of YBCO.

"The alliance's work on coated conductors provides American Superconductor with a potential second generation of wire technologies for additional business growth in the next decade," says Gregory Yurek, ASC's founder, chairman, and CEO. He notes that over the next four years, the company will introduce significant HTS product lines based on its current generation of bismuth-based wire technology.

The next-generation wire alliance will extend for four years. ASC and EPRI intend to provide combined funding of about $5 million to the alliance during the first two years. ASC will receive exclusive marketing and manufacturing rights to technologies developed under the alliance, while EPRI will receive warrants for an equity stake in ASC in proportion to the Institute's investment in the alliance's technology development.

According to Grant, the ASC-EPRI alliance will work with the Los Alamos and Lawrence Berkeley laboratories as well as with Inco Alloys International (ASC's strategic partner), Stanford University, and the Applied Superconductivity Center at the University of Wisconsin. There are also plans to work with Oak Ridge, the Wright Laboratory at Wright-Patterson Air Force Base, the Massachusetts Institute of Technology, and the Texas Center for Superconductivity at the University of Houston.

Charles Curtis, U.S. deputy secretary of energy, says, "The collaboration between the ASC-EPRI alliance and the national laboratories is an exciting example of how basic technologies successfully developed under the DOE superconductivity program can lead to commercial applications." □

The development of a prototype HTS transmission cable is proceeding ahead of schedule in a partnership involving the cable manufacturer Pirelli, ASC, EPRI, and DOE's SPI. Last March, Pirelli announced that it had successfully assembled a 50-meter flexible stranded conductor from several kilometers of ASC's multifilament BSCCO wire, using an industrial cable-winding machine at its South Carolina factory. The prototype conductor assembly exceeded the design target with a critical current density of 1800 A dc at 1 μV/cm² in liquid nitrogen.

According to Don Von Dollen, manager for underground transmission in EPRI's Power Delivery Group, Pirelli's 50-meter prototype conductor signals the beginning of the industrial phase of HTS cable manufacturing. "They can now make any length of conductor they want," he notes. Engineers expect that lengths of HTS cable are likely to be connected by joints to form an underground transmission circuit. Refrigerators and coolant pumps would be located at the ends of the system and perhaps at intermediate joints, depending on length.

Mujibar Rahman, Pirelli's vice president and chief R&D engineer, says that the company expects to beat a 1998 target for completing and testing a 30-meter ac prototype HTS cable system that will include joints and terminations. The cable will consist of a hollow stranded-conductor assembly—through which liquid nitrogen will circulate—surrounded by cryogenic and electrical insulation. Three cables (for three-phase transmission) will be contained in an 8-inch steel pipe, along with related terminal connections. The performance target for the complete cable prototype is to carry 2000 A ac when energized at 115 kV. An earlier 1-meter prototype achieved 4200 A dc.

"Pirelli is committed to leading the market in power transmission cables, and HTS cable technology is an important element of our strategic business plan," says Giuseppe Morchio, chief executive of the Milan, Italy-based company's Pirelli Cables group. Pirelli and ASC say that they expect to test commercial HTS power cables in 1998–1999 and to begin marketing them to electric utilities by 2000. Pirelli and EPRI have already begun independent studies with individual utilities to assess the operation and impact of HTS circuits in transmission systems.

Other ventures are pursuing HTS power cables for different types of retrofits and for new applications. In an effort with DOE, Oak Ridge, and Intermagnetics General, Southwire has developed and tested a 1-meter prototype at 2000 A ac. Last year Britain's BICC Cables, its Italian subsidiary (CEAT CAVI), and Ansaldo Ricerche said that they had tested a 1-meter dc prototype. It was made with BSCCO wires from Intermagnetics and carried 11,000 A at 20 K.

In Japan, Tokyo Electric Power Company (TEPCO) is heading two collaborations with major Japanese electrical equipment and HTS technology companies to develop compact HTS transmission cables with capacity ratings of 500 MW to 1 GW. Such cables could be used to replace and uprate existing underground lines serving Tokyo without the need for larger tunnels. The collaborations, with Sumitomo Electric Industries and Furukawa Electric, have produced and tested 50-meter cable prototypes.

TEPCO and Sumitomo recently tested a 50-meter prototype power cable fabricated from BSCCO wires that carried 2900 A dc and 2200 A rms at 77 K. Earlier, TEPCO and Furukawa conducted a 15-minute continuous load test at 2000 A and 69 kV to assess a 5-meter single-phase HTS cable equipped with termination connections.

Transformers

The equipment used to step up or step down the utility circuit voltage from one level to another, either at the high levels of long-distance transmission or at the lower levels employed for local distribution, is also of interest for HTS application. Superconducting materials would reduce resistance losses (although not intrinsic ac-related losses), and they have other features that add to their appeal.

Because transformers are used at such a wide range of voltage and capacity ratings, markets for them vary throughout the world. Large, high-voltage transformers with reduced losses and improved efficiency have long been a focus of R&D in this country, but the domestic market for them is stagnant. Lower-voltage prototypes are a logical common starting point for the development of either distribution or high-voltage HTS transformers. One feature of HTS transformers that may drive interest in them is that the liquid nitrogen coolant is environmentally superior to other alternatives.

In 1994, ASC began shipping BSCCO wire to Switzerland, where the global electrical and engineering conglomerate ABB Asea Brown Boveri is a partner in a venture that is building a 630-kVA three-phase HTS transformer. Other partners are SIG (Geneva's electric utility), a Swiss utility research consortium, and Electricité de France. Plans call for testing the prototype, which will operate with liquid nitrogen cooling, late this year on the Geneva power grid in order to assess its operating benefits and reliability. Commercially viable HTS transformers are expected to have ratings of several tens to 100 MVA.

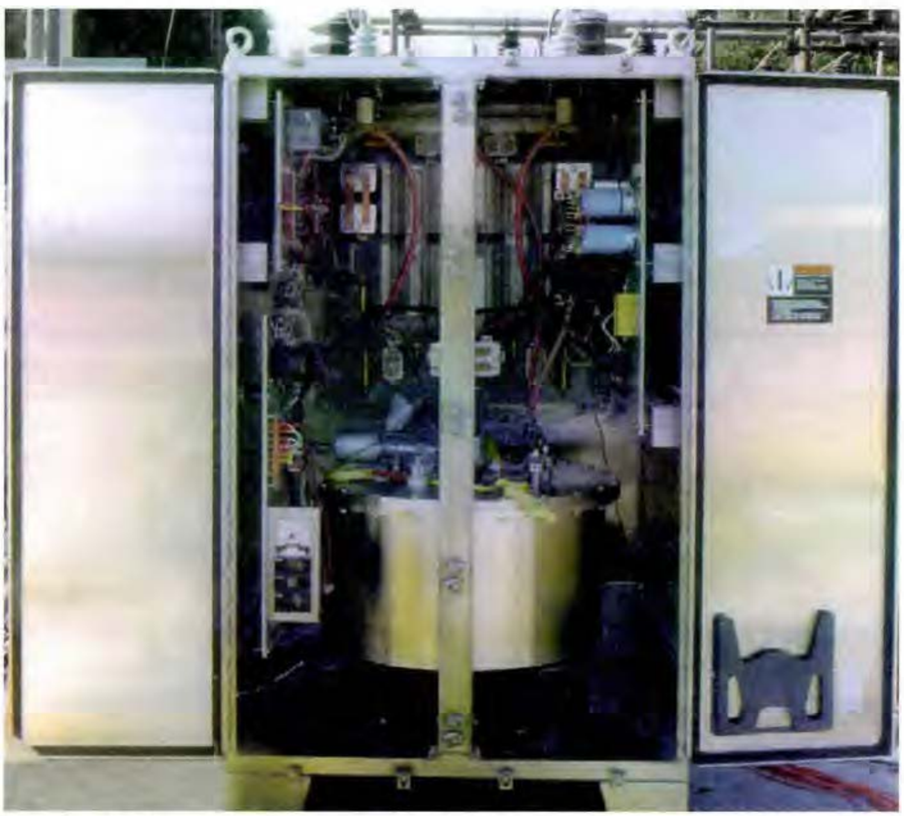
In Japan, Sumitomo—in collaboration with Fuji Electric and Kyushu University—has developed and tested a 550-kVA transformer prototype that uses BSCCO conductor and operates at 77 K.

In the United States, Intermagnetics General and Wisconsin-based Waukesha Electric Systems are collaborating with Rochester Gas and Electric Corporation and Oak Ridge National Laboratory to build a demonstration transformer using BSCCO conductor. The unit would operate as a test bed at 20–50 K with cryocooling. The team has produced two 138-kV, 30-MVA three-phase reference designs that it believes will be cost-competitive with conventional transformers while weighing half as much and having smaller footprints. The companies expect to begin testing a 1-MVA single-phase demonstration unit in January.

Power system control and protection

Superconducting fault current limiters could afford utility equipment (e.g., breakers, fuses, switches) greater protection against large momentary power spikes caused by short circuits or lightning. Moreover, such devices could provide utilities a

SUPERCONDUCTING MOTORS ARE GETTING BIGGER **Reliance Electric (a subsidiary of Rockwell Corporation) and American Superconductor demonstrated a 200-hp HTS motor earlier this year as part of DOE's Superconductivity Partnership Initiative. Centerior Energy, EPRI, Sandia National Laboratory, and Rockwell Automation's Gainesville, Florida, motor plant were represented on the development team. Only three years ago, Reliance built and demonstrated a 5-hp HTS motor with EPRI support. The new 200-hp motor, built with BSCCO-wire-based rotor coils from American Superconductor, was operated at 1800 rpm at 27 K. Rockwell's goal is to commercialize large industrial HTS motors; next it plans to demonstrate a 1000-hp motor and, by the year 2000, a 5000-hp precommercial prototype.**



HTS FAULT CURRENT LIMITER TESTED AT SCE **Southern California Edison and EPRI are collaborating with Lockheed Martin to develop and test a 15-kV three-phase HTS fault current limiter. Such devices could help protect utility substation equipment from short circuits and lightning as well as improve power flow management. Last year SCE successfully tested a 2.4-kV, 2.2-kA single-phase fault current limiter from Lockheed Martin at one of its substations.**

way to interconnect parts of distribution systems more tightly and to manage power flows more effectively with less redundancy of protective equipment and substation capacity. Such extra capacity is now maintained in order to limit the maximum potential fault current on any particular circuit.

Working under the DOE-led SPI, Southern California Edison Company (SCE) and EPRI are collaborating with Lockheed Martin in a two-year effort to develop and test a 15-kV three-phase HTS fault current limiter. The effort includes Intermagnetics General and Los Alamos National Laboratory. Last year SCE tested a 2.4-kV, 2.2-kA single-phase fault current limiter made by Lockheed Martin. At the heart of the device was a coil wound from BSCCO wires supplied by ASC. In an energized equipment test facility at SCE's Center substation in Downey, the prototype met or exceeded all design targets.

Lockheed Martin is interested in commercializing HTS fault current limiters for the utility market. According to a survey of HTS applications R&D earlier this year in *Physics Today*, other teams of electrical equipment manufacturers and electric utilities around the world—including GEC Alsthom and Electricité de France, Toshiba and TEPCO, and Siemens and Hydro Québec—are also developing such devices.

Motors and generators

Rotating electrical equipment depends on rotor windings or solenoid coils that can generate strong magnetic fields as part of normal operation. Such fields can be achieved with BSCCO-wire-based rotor coils operated at 20–40 K, and such coils are expected to provide cost-effective commercial motor performance. If YBCO-coated conductor tape is successfully developed, it could offer the further benefit of permitting operating temperatures around 77 K. In the meantime, although commercial BSCCO-based HTS wire shows relatively poor performance at 77 K in high magnetic fields, its properties are sufficient to enable significant progress in the engineering development and scale-up of prototypes for both HTS motors and generators.

Electric motors are used extensively by

SUPERCONDUCTING RACETRACK FOR AN HTS GENERATOR **A team of specialists at General Electric's R&D Center in Schenectady, New York, designed, built, and successfully tested this prototype HTS generator racetrack coil earlier this year. The coil was made from some 2400 meters of BSCCO tape manufactured by Intermagnetics General Corporation. Suspended in a vacuum and cooled with helium gas, the coil was tested at temperatures ranging from 16 to 77 K. It achieved steady-state currents of 34 A at 25 K and 30 A at 20 K. The coil was produced as part of the first phase of a government-industry program targeting the development of high-efficiency, low-cost HTS generators for electric utilities.**

utilities and others. They are ubiquitous, consuming more than 55% of all the electricity generated in the United States. And large motors (>1000 hp) account for more than half of that consumption. ASC believes that HTS motors will provide such compelling benefits and operating advantages that they could eventually dominate the global market for large motors, which now exceeds $1 billion a year. HTS motors are expected to be half the weight and half to one-third the size of conventional motors, to be much quieter, and to offer lower operating costs.

Earlier this year, under the SPI, Rockwell Corporation's Reliance Electric subsidiary and ASC demonstrated a 200-hp HTS motor. Its power output was increased by 60% over the original design goal, in part on the basis of knowledge gained in demonstrating a 5-hp motor with EPRI support just three years ago. The 200-hp motor, built with BSCCO-wire-based rotor coils developed and made by ASC, was operated at 1800 rpm at 27 K. Centerior Energy Corporation, EPRI, Sandia National Laboratory, and Rockwell Automation's Gainesville, Florida, motor plant participated on the development team.

The next goal of the continuing joint development effort is to demonstrate larger units, first a 1000-hp motor and then, by the year 2000, a 5000-hp precommercial prototype. Rockwell says that it plans to commercialize large industrial HTS motors in four to five years. Meanwhile, U.S. Navy research engineers have developed and tested both LTS and HTS motors, including a test-bed unit equipped with a BSCCO coil from ASC.

As a result of the progress demonstrated with the 200-hp Reliance motor, Kurt Yeager, EPRI president and chief executive officer, was quoted in the Reliance announcement in March as saying that he expects to see 5000-hp HTS motors in use by utilities by the start of the next decade and even larger superconducting motors soon thereafter. "The payoff will be lower electricity bills for utilities and industry," said Yeager. "For example, a conventional 10,000-hp motor that uses copper wire coils is about half the size of a bus. An HTS motor of the same power will have half the volume and weight and will save about $100,000 a year in electricity costs. EPRI is proud to have been the catalyst in the developments that led to this milestone."

Generators: déjà vu

Utility interest in a superconducting generator actually predates the discovery of HTS materials a decade ago. By 1986, EPRI, equipment vendors, and federal energy research organizations were winding down a series of collaborative efforts to develop an LTS generator. Commercial designs for 300-MVA units were envisioned in a project that included Westinghouse, EPRI, the Tennessee Valley Authority, and the Massachusetts Institute of Technology. Separately, in the early 1980s, General Electric developed and successfully load-tested a 20-MVA prototype (built with five rotor coils of NbTi wire) with liquid helium cooling. But an LTS generator was never commercialized because its overall economics did not appear favorable for development as a competitive product.

Now, however, the availability of high-current HTS wires and coils could change the technoeconomic prospects. GE has been quietly working under the SPI to develop and test an HTS coil for use in a generator rotor. After acquiring more than 2 kilometers of BSCCO flat-tape wire from Intermagnetics General, GE laminated the tape with copper for greater strength and wrapped it with paper insulation. The researchers then wound the tape in a layered, continuous racetrack coil designed to produce about 35,000 ampere-turns of magnetomotive force and to be capable of operating in a 1.5-MVA generator. GE tested the insulated coil first at liquid nitrogen temperature, at which it carried 5–10 A. But suspended in a vacuum and cooled with helium gas to 20 K, the coil carried about 34 A at steady state and was briefly ramped as high as 60 A.

Kenneth Herd, a mechanical engineer in the GE R&D Center's applied superconductivity program, says that the researchers are working with DOE and GE's Power Systems group to pursue rotating tests of the coil. In these tests, the coil would be mounted in a rotor with an armature and stator assembly to verify operation at 3600 rpm as a prototype 1.5-MVA generator. GE sees "distinct cost advantages of being able to operate at 20 K instead of liquid helium temperature," notes Herd, as well as "other profound advantages of design" that could lead to a new paradigm for superconducting generators. "For the first time, we can see the potential not only for higher efficiency and perhaps lower weight but also for lower capital costs."

The U.S. Air Force is also developing a high-density, lightweight HTS generator —for use on aircraft—in a program centered at Wright-Patterson Air Force Base's Wright Laboratory. ASC has been delivering BSCCO wire coils to the laboratory since 1992 for use in a 1-MVA prototype.

In Japan, several large electric equipment manufacturers are participating in a major superconducting generator project. Called Super GM, the effort is organized by the country's Ministry of International Trade and Industry. The LTS generator will have NbTi coils and operate at liquid helium temperature. The project reportedly has nearly completed a 70-MVA prototype at Kansai Electric Power's Osaka station and plans to begin testing of the machine this year. Commercial HTS generators are expected to have ratings of 200 MVA or more.

Maglevs and more

High-field HTS magnets could open up an entirely new realm of applications both within and beyond the utility industry, with potentially even broader social impacts than those already glimpsed for the near future.

In Japan, railway research engineers are considering whether to make a major new push to develop magnetic levitation (maglev) trains—prototypes of which with LTS magnets have been successfully tested—or to focus instead on developing a new generation of the country's 30-year-old bullet train technology. Observers expect that high-field HTS magnets would be used in place of LTS magnets if maglev is targeted for major development.

At the Texas Center for Superconductivity at the University of Houston, HTS researchers have made magnetic bearings with melt-textured single-crystal YBCO. Such bearings could be used to reduce the loss of rotational force in large flywheels that, in turn, could be used both to store energy and to absorb power fluctuations in utility and customer applications. The bearings are expected to be simpler and less costly than the so-called active magnetic bearings used today in some rotating machines. Japan's Chubu Electric Power and Dowa Mining reportedly are also working on developing and reducing the cost of producing single-crystal YBCO chips for magnetic bearings. Other research groups in Japan have produced magnetic-flux-trapping YBCO disks that can levitate by several inches large permanent magnets with people standing on them.

Related applications of high-field HTS materials include large- and medium-capacity superconducting magnetic energy storage (SMES) systems. SMES designs based on the use of large-diameter, liquid-helium-cooled NbTi LTS conductor coils have been developed under government R&D programs in this country. Such designs could be adapted to use HTS conductors at 20–40 K. Meanwhile, microcapacity SMES units—some with helium-cooled LTS coils and others with HTS coils cooled with liquid nitrogen—are already being commercialized by a number of firms for protecting sensitive industrial and commercial loads from momentary power glitches or interruptions. Commercial developers include Superconductivity, Inc., and ASC.

Toward a superconducting future

It is ironic, although perhaps of little significance for the prospects for practical applications, that "we still don't know the mechanism of superconductivity at high temperatures," says Grant. "High-temperature superconductors are believed to involve paired electrons, as do their low-temperature counterparts, but we don't really know what holds the electrons together in the HTS materials. This is why, even 10 years after the discovery of these high-temperature materials, superconductivity is still at the leading edge of condensed-matter physics."

The many ongoing and approaching HTS prototype developments are solid evidence of the rapid progress from discovery to demonstration that has been made in only a decade's time. It appears ever more likely that superconducting machines and power cables will be operating on utility systems by early next century. These prototypes will provide the technical data and operating experience that will determine whether the still-mysterious but marvelous scientific curiosity of high-temperature superconductivity can indeed be the basis for utility power systems of the future. ■

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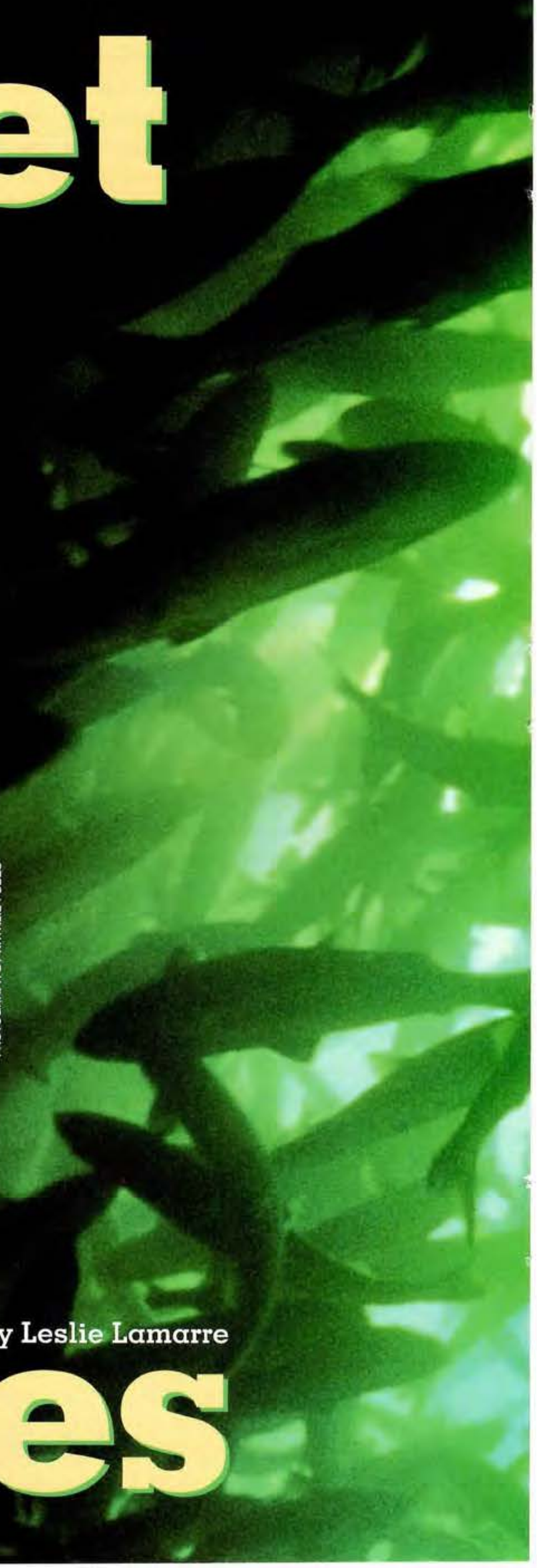
Background information for this article was provided by Paul Grant of Strategic R&D and Don Von Dollen of the Power Delivery Group.

Fish Market

THE STORY IN BRIEF

Aquaculture, or fish farming, is on the brink of becoming big business in the United States, and electric utilities across the country are gearing up to get involved. Not only does fish farming mean increased electricity sales and economic development within utility service territories, it could also bring more jobs into the country and help struggling farmers stay in business. The potential for extra income through the sale of power plant waste heat and the leasing of utility land is adding to the lure. The aquaculture industry has some problems to overcome, however, including inefficient fish production systems. In hopes of setting a technology standard to revolutionize large-scale fish production, EPRI is sponsoring the demonstration of a computer-controlled aquaculture module that employs a number of sophisticated electrotechnologies.



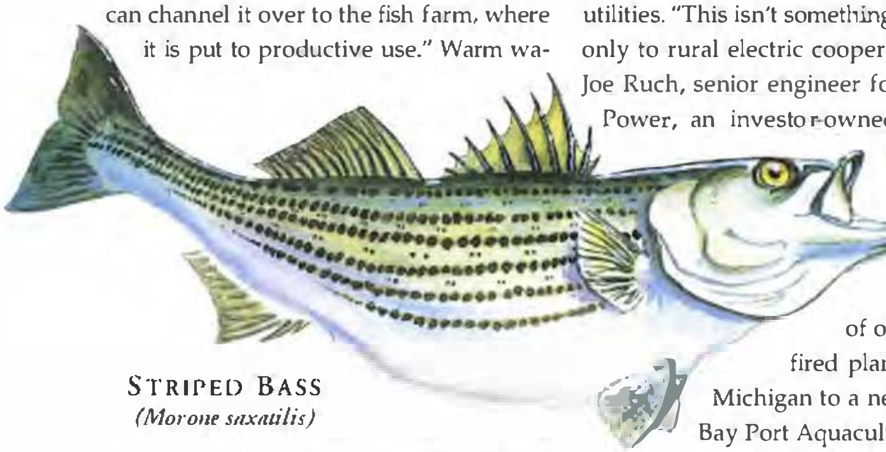
PHOTOGRAPH BY NATALIE FOBES

Lures Utilities

by Leslie Lamarre

It's winter on the wind-whipped plains of North Dakota, and temperatures well below zero are packing emergency rooms with frostbite victims. But thousands of warm-water fish are thriving in the central part of the state. In fact, hundreds of these African fish, called tilapia, are harvested for eating every day. Welcome to Golden Fisheries, one of this country's successful fish-farming operations. Located near a coal-fired power plant some 80 miles northwest of Bismarck, the fish farm uses the power plant's waste heat to keep its tilapia toasty year-round. The resulting yield supplies processors in New York and Chicago, helping to meet—even in the off-season—this country's voracious appetite for seafood.

"It's a neat concept," says Jim Selby, business development coordinator for Basin Electric Power Cooperative, owner of the 900-MW coal plant. "Rather than blowing this heat up into the air and wasting it, we can channel it over to the fish farm, where it is put to productive use." Warm water is piped through about half a mile of conduit and arrives at the fishery at about 100°F—warm enough to please the fish and heat the air inside the 2-acre dome structure where they are raised. Although the fishery has a supplemental heat source for emergencies, heat from the water usually suffices—even in the arctic cold of the winter months. The fishery has operated at the site for four years, employs about 13 people, and consumes 4.1 million kWh of electricity annually—about as much as a small town.



STRIPED BASS
(Morone saxatilis)

FISH ILLUSTRATIONS BY NORMAN KEKKI

Electricity sales and economic development are just two of the incentives that have gotten power companies such as Basin Electric involved in aquaculture over the years. Utilities like the steady load of such round-the-clock operations. And opportunities for earning extra income through the sale of waste heat and the leasing of land make aquaculture even more attractive to utilities. "This isn't something that pertains only to rural electric cooperatives," notes Joe Ruch, senior engineer for Consumers Power, an investor-owned utility that pipes warm water discharge from the condenser of one of its coal-fired plants in western Michigan to a neighbor called Bay Port Aquaculture. This fish farm raises yellow perch—a species native to the area that thrives in 70°F water—and sells them to local processors. The company leases a 10-acre parcel from the utility and has operated at the site for six years. During that time, it has grown steadily to its current annual production capacity of 100,000 pounds. "Electrical load is a prime interest from our perspective," says Ruch. "There's an excellent market for yellow perch in this area, and there's a potential for this business to expand into processing, which would mean new refrigeration plants."

Rather than blowing this heat up into the air and wasting it, we can channel it over to the fish farm, where it is put to productive use.

Jim Selby, Basin Electric Power Cooperative

Not all utility-related aquaculture endeavors have been so successful. In fact, a number of well-publicized failures have somewhat soiled the industry's reputation. But with the aquaculture industry on the brink of what many experts say will be a significant boom, the electric utility industry is showing renewed interest in these operations. According to EPRI's *Aquaculture Scoping Study* (CR-105302), published in May 1995, aquaculture is the fastest-growing sector of U.S. agriculture. The study reports that world fisheries are now at or above sustainable yields and that global aquaculture must increase sevenfold in the next 35 years in order to keep up with the demand from a growing population. The industry is particularly ripe for development in this country, where health consciousness and other factors have increased the consumption of seafood. At this time, production from U.S. fish farms accounts for only 3% of the global aquaculture harvest. Meanwhile, the United States is the world's second-largest importer of seafood products. These imports total nearly $9 billion annually, making seafood our third-largest import, behind oil and automobiles.

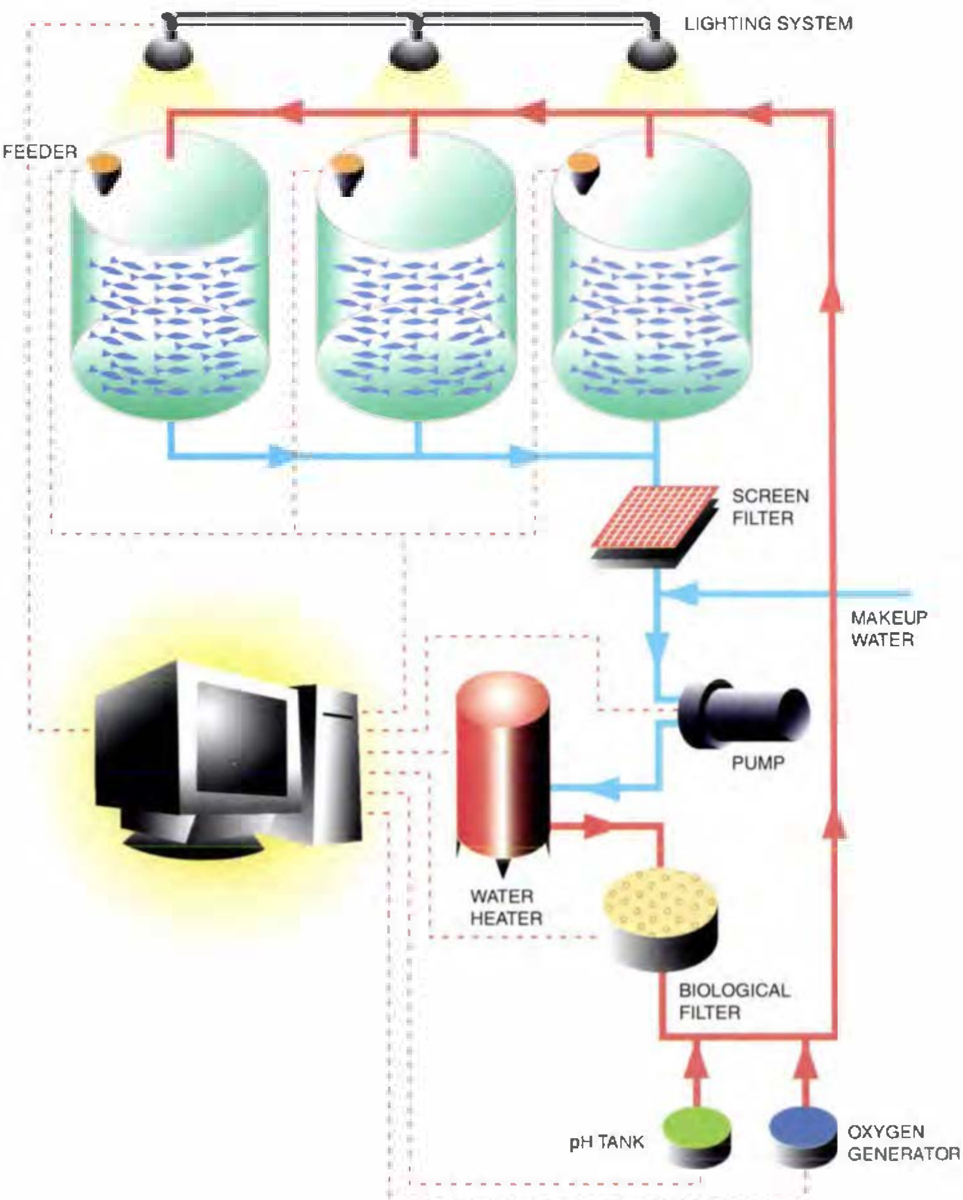
The scoping study, undertaken because of the great potential for utility involvement in the rapidly growing aquaculture industry, highlights opportunities for utilities to nurture this beneficial customer base. The study was a recent project of EPRI's Agricultural Technology Alliance, established two years ago to support various types of farming in the United States. "Utilities often don't recognize the significance of their agricultural customer base; in many cases it's hidden, since a number of these farms are on a residential rate," says Myron Jones, who manages EPRI's agriculture research. At the same time, U.S. farmers face serious challenges that threaten to move food production into Mexico and other countries. "Aquaculture," notes Jones, "is something that struggling farmers could do as a sideline, using barns, land, and other equipment they already own." The only catch is the need for a large water supply. However, advanced water recirculation technology does away with this need, allowing aquaculture to be conducted just about anywhere. Says Jones, "You could have a production facility in an urban warehouse just as well as in a remote rural location."

New directions

Traditional aquaculture, which employs either natural settings like ponds or artificial vessels like raceways, requires access to a significant water source because typically the water flows through the system only once before it is discharged. In contrast, recirculating aquaculture systems literally recirculate the water used so that daily water discharge is minimal. According to Jonne Berning, a fish farmer and an aquaculture consultant for EPRI, a recirculating system with an annual capacity of 100,000 pounds of fish uses only 1000 gallons of water daily—about three times the typical household use of a family of five.

YELLOW PERCH
(Perca flavescens)

CAREFUL CONTROL Computer monitoring enables optimal fish growth in advanced recirculating systems like the one that EPRI and other cosponsors plan to demonstrate. Used water, pumped continuously from the tanks where the fish are grown, passes through a screen filter, which catches such debris as fish waste and food particles. Water temperature, chemical balance, and oxygen level are all adjusted before the water flows back to the growing tanks. A regulated lighting system provides the appropriate illumination. On a daily basis, only 5–10% of the water in recirculating systems needs to be replaced with makeup water.



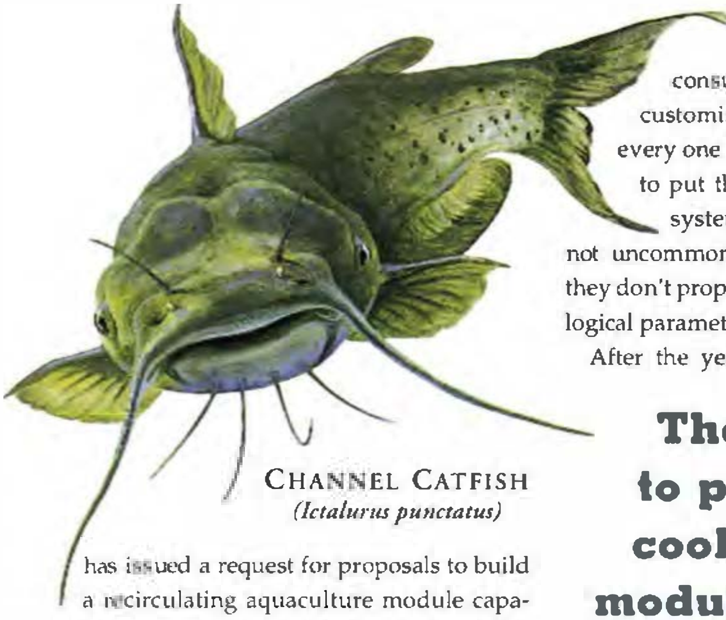
SCHEMATIC BY ANTHONY LUKBAN

A nonrecirculating system with the same capacity uses about 25 times this amount of water. The minimal water discharge from recirculating systems not only offers flexibility in facility siting but also makes it easier to obtain the necessary environmental permits for operation.

Unlike traditional aquaculture operations, which are often open to the air, recirculating systems are enclosed, offering optimal control over the biological environment, so chances of invasion by a deadly virus or of exposure to toxic substances like mercury are slim. In fact, careful monitoring by computer enables fish farmers to track exactly what their fish eat, so the ultimate product is not only healthy but better tasting. For instance, catfish raised in ponds can wind up tasting muddy if certain algae build up in the water. With a recirculating system, farmers can easily monitor and control algae buildup to avoid this problem.

But the most obvious advantage of recirculating systems is that they are far more efficient at fish production. Constructed either with a raceway or in a circular tank configuration, recirculating systems employ automatic feeders and air blowers to provide as much food and air as required for the number of fish in the system. Waste-laden water flows through biological filters that clean it. While a nonrecirculating system typically produces 3000 pounds of catfish per acre, a recirculating system yields 100,000 pounds per acre.

Through a current project initiated by the Agricultural Technology Alliance, EPRI



CHANNEL CATFISH
(Ictalurus punctatus)

has issued a request for proposals to build a recirculating aquaculture module capable of producing 100,000 pounds of fish annually—the minimum capacity believed to be economically viable for aquaculture. Plans are for the demonstration to run for one year, during which conditions will be optimized. The experience will be documented in a series of how-to manuals covering the details of building and operating such a facility, including the costs involved and the return on investment that can be expected. Specifications for optimal growing conditions, such as water temperature and feed rate, will be included for various kinds of fish.

"The goal is to produce a cookie-cutter module that will work in any part of the country—regardless of whether you want a 100,000-pound-per-year facility or a million-pound-per-year facility," says Berning. Although the demonstration module will be used to grow tilapia, the plan is to make it a system that can be used for other types of fish as well. Says Berning, "Our aim is to get the system down to a science so that whether you want to grow tilapia in Florida or hybrid striped bass in North Carolina, you should be able to use the same system with minimal modifications."

If successful, the demonstration could set a standard for aquaculture system design that would make it possible to mass-produce fish for the market, much as chicken is produced today. At this time, no such standard exists. As Berning explains, "There are so many consultants out there hawking customized systems, and almost every one of them has a different way to put these systems together. The systems are not cheap, but it's not uncommon for them to fail because they don't properly account for certain biological parameters, like oxygen."

After the yearlong demonstration, the facility could be used for training people in the aquaculture business who would like to operate such systems of their own. And utilities could serve as an information resource for customers who might be interested in establishing their own systems. EPRI expects to select a contractor and a host site for the demonstration by the end of this year. The project could cost up to $500,000, of which EPRI has committed $80,000. (The capital cost of a commercial system would be considerably less, averaging about $200,000 for a facility with a 100,000-pound annual capacity.) EPRI is seeking cofunding from aquaculture businesses and electric utilities. If the funding is sufficient, a second demonstration project could be initiated.

The goal is to produce a cookie-cutter module that will work in any part of the country—regardless of whether you want a 100,000-pound-per-year facility or a million-pound-per-year facility.

Jonne Berning, fish farmer and aquaculture consultant

Recirculating aquaculture systems employ a multitude of electrotechnologies, including pumps for circulating the water continuously, air compressors or oxygen generators, and artificial lighting. On average, a well-designed system of this type uses about 5000 kWh of electricity per month. This does not include energy used for heating, since in most cases this need is served by natural gas or propane. "While a single facility might not sound like much, by the time you put 10 or 20 of these into one utility's service territory, the kilowatt-hours start adding up," says Berning. Additionally, there are a number of advanced electrotechnologies—for example, ozonation for water disinfection, computer-related controls, and energy-efficient lighting—that could be employed to enhance such systems. Some of these technologies will be used in the tilapia demonstration module.

FISH DOME **This 2-acre, air-supported dome structure in North Dakota houses tanks and raceways for growing a hearty warm-water fish called tilapia. Golden Fisheries, which owns and operates the facility, gets its supply of warm water from a coal plant across the road. The plant is owned by Basin Electric Power Cooperative.**

Utility efforts

A number of utilities that already recognize the benefits of aquaculture have embarked on their own research projects. New York State Electric & Gas Corporation is sponsoring the development and construction of a small-scale aquaculture system that will enable this science to be taught at one of the state's two-year technical colleges. Plans are for the system to be ready for use this fall. "Aquaculture is an expanding enterprise that may provide new opportunities for some of our small dairy farmers that are being squeezed out of business by competition from bigger companies," says Richard Peterson of NYSEG's agricultural energy services group. "These farmers have resources on their property, such as buildings, that could be converted for closed-system aquaculture."

The Tennessee Valley Authority, which has conducted 15 years of research on tilapia production, is currently working on a project to evaluate the feasibility of using mineral- and nutrient-laden wastewater from an aquaculture facility to grow a variety of crops, from vegetables to high-value ornamental crops like azaleas and other flowers. According to Les Behrends, a manager with TVA's Environmental Research Center, the crops could be grown either in a wetland environment outdoors or in a hydroponics greenhouse for year-round production. The advantage of hydroponics is that it enables a more rapid growth rate, partly because plants can absorb nutrients faster from water than they can from soil. As the plants gather their nourishment, they also act as filters, clearing the waste from the water. (See the sidebar for more details on hydroponics systems.) The primary interest for TVA, as for NYSEG, is economic development. "If we can demonstrate the feasibility of the indoor farms, there are a lot of areas in the Southeast where such operations could be sited," says Behrends.

Interest in economic development has also spurred Carolina Power & Light Company into action. For the past three years, CP&L has collaborated with North Carolina State University to demonstrate the feasibility of growing fish in an aquaculture system housed in a metal-sided barn typical of those found in the region. This effort dates back to 1990 and was initiated by the university with funding from the energy division of the state's Department of Commerce. According to Tom Losordo, an associate professor with the university, the school's cooperative extension system had received many inquiries from local farmers and entrepreneurs who were looking for information on using barns for growing fish. Alex Hobbs, a principal engineer in CP&L's research section, says he had received similar calls over the years. "We have a good infrastructure of feed mills, processing plants, and farms in our area to support this kind of industry, so we thought a local demonstration was a good way to see how it might work," he says.

	Nonrecirculating	Circulating
Land area	45 acres	1 acre
Water use	25,000 gal/day	1000 gal/day
Electricity use	0.001 kW/lb	0.045 kW/lb
Maturation period	18 months	12 months
Yield	3000 lb/acre	100,000 lb/acre

THE RECIRCULATING ADVANTAGE Although recirculating aquaculture systems use more electricity than traditional fish-farming operations, they offer a number of advantages, such as dramatically higher yields. The relatively small water supply and land area required for recirculating systems mean that they can be located just about anywhere. And because the systems are enclosed, they offer protection from pollution and disease.

Housed in a barn on the campus of North Carolina State University in Raleigh, the demonstration system produced 24,500 pounds of tilapia in 1993, reflecting a survival rate of 94%. Since then, researchers have retrofitted the system with recirculating technology that they believe will show even better results. Tests of the new system are under way. Hobbs notes that this technology is of particular interest to his utility because it enables aquaculture to be practiced in parts of the state that do not have large water resources. In addition to supporting the project financially, CP&L has served as an advisor on the electrotechnologies employed and has worked to ensure the energy efficiency of the system.

Opportunities abound

While research continues to enhance aquaculture production, there are plenty of commercial establishments already up and running, providing ample opportunity for utility benefits. Take, for example, the case of Jackson County Rural Electric Membership Corporation in Indiana. A shrimp company approached the co-op last fall about establishing an extensive shrimp-growing operation on farmland within the co-op's service territory. The company, Penbur Farms, has since purchased 50 acres of this property (currently a cornfield) and has the option to buy another 50. Plans are to construct up to 11 buildings in which the shrimp will be grown. Pumps to circulate the water, artificial lighting for optimal shrimp growth, air conditioning, and ultraviolet light for water disinfection are just some of the operation's electricity needs. The total potential electrical load is 7 MW, or more than 5% of the co-op's existing electrical load, says Brian Wolka, member services director for the co-op. This assumes that the facility will use propane for heating.

PENNYFISH TILAPIA
(T. hornorum/T. mossambica hybrid)

The use of utility land and waste heat offers opportunities for more-direct utility involvement and for environmental benefits. Such is the case with projects involving Basin Electric Power Cooperative and Con-

Vegetables Too Can Thrive Indoors

Just as fish farming can be conducted indoors under controlled conditions for more-bountiful yields, so can plant farming. Plant production through controlled-environment agriculture (CEA) involves levels of precision, control, and productivity that go well beyond the capabilities of traditional greenhouse farming. With funding from several sponsors—including EPRI, New York State Electric & Gas, New York State Energy Research and Development Authority, and Empire State Electric Energy Research Corporation—researchers at Cornell University aim to refine CEA plant production and jump-start an indoor farming industry in the United States.

At this time, a small number of greenhouses are used for growing vegetables in this country. According to Louis Albright, a professor of agricultural and biological engineering at Cornell, these facilities are often operated by small producers with little of the marketing experience necessary to find consistent buyers for their produce. As a result, the bulk of the warm-weather vegetables bought by consumers during the winter months are imported from elsewhere in the United States or from other countries. Keeping such production in the United States through the use of CEA facilities would not only keep jobs in this country but also enhance the quality of out-of-season produce, says Albright.

For electric utilities, CEA facilities mean increased electricity use through artificial lighting, air circulation, computers, and other loads. Better still, the round-the-clock nature of these facilities makes it feasible for at least 70% of the load to be off-peak and to be interruptible for short periods. "The use of successful CEA facilities would essentially convert the liquid fuel costs currently incurred in transporting vegetables into electricity costs to grow the vegetables locally," Albright says.

The Cornell researchers have already successfully tested a laboratory-scale model of a CEA hydroponics system for growing lettuce. Hydroponics systems, in which plants are grown in a nutrient solution rather than in soil, are already widely used for growing lettuce. However, the precise environmental control enabled by such CEA technologies as artificial lighting and air circulation is not available through conventional hydroponics systems. With the help of their sponsors, the Cornell researchers plan to establish a full-scale CEA hydroponics demonstration module for growing a variety of marketable plants, from vegetables like tomatoes to high-value crops like herbs. According to Albright, the researchers will start out with Bibb lettuce—one of the easiest vegetables to grow. The goal for the 8000-square-foot facility is to churn out 1000 heads of lettuce daily. Research results have determined the ideal temperatures and levels of nutrients and dissolved oxygen for producing such a yield.

The lettuce will be started from seed in a "growth room," with the help of artificial lighting. On the eleventh day, the seedlings will be transferred to Styrofoam rafts floating in four ponds, each measuring 100 feet by 20 feet. The rafts allow the plants' roots to extend into the hydroponics solution so that they can draw nutrients from the liquid. According to Albright, the lettuce will be ready for harvesting on the thirty-fifth day. Careful control of environmental conditions enables this rapid growth rate in any season. With more-traditional hydroponics methods, in contrast, Bibb lettuce can take up to 80 days to mature during the winter months. As with recirculating aquaculture systems, CEA vegetable farming offers the advantage of protection from diseases and other stresses in the natural environment.

Plans are for the CEA facility, which will be established in upstate New York, to be operational this fall. As with the EPRI-sponsored aquaculture demonstration facility, the CEA demonstration will run for one year. After that, the facility will be used for training growers who want to run their own CEA operations as franchises. Under the direction of an agriculture cooperative, the facility will serve as a model for the franchises. The cooperative will handle the marketing such franchises would require and will provide them with supplies, leaving the nuts and bolts of the production operations to the growers themselves. The cooperative will also be responsible for keeping the growers abreast of computer programs and other new technologies to enhance production. □

sumers Power, in which the use of utility land and waste heat has led to a symbiotic relationship between power plants and fish farms. However, some utilities caution that allowing aquaculture establishments and other businesses to use utility land can be difficult. For example, utility regulators in many states have not allowed investor-owned utilities to enter into the long-term leases of 10–20 years that would be required for an aquaculture business. The rationale is that the utility must be able to recover its land on short notice (anywhere between 30 and 180 days) in the event that there is a need to expand a facility or extend transmission lines. For an aquaculture business that may have made a $3 million capital investment on the site, that isn't much time. Besides, banks typically won't loan money to finance aquaculture facilities under such conditions.

GOOD NEIGHBORS Power plants and fish are a great mix in western Michigan, where Bay Port Aquaculture leases land from Consumers Power and uses warm-water discharge from one of the utility's coal plants to raise yellow perch. Shown here are the coal plant (as seen from the fishery) and Bay Port's outdoor raceways, where netting helps ward off local seagulls.

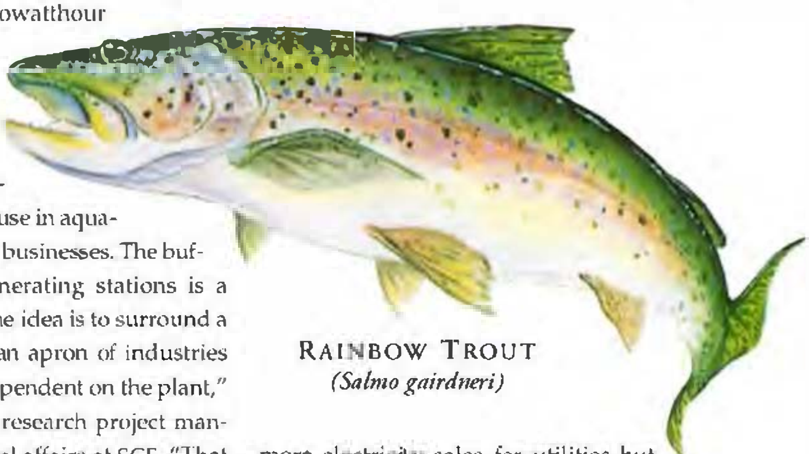
More aquaculture in the United States means not only more electricity sales for utilities but more jobs for the economy and fewer fish imports.

Myron Jones, EPRI

The good news is that deregulation of the electric utility industry is changing this scenario—at least for some utilities. Increasing competition is encouraging utilities to maximize their assets, including underutilized land. And public utility commissioners are relaxing their grip. According to Andy Harpster, a land management expert with Southern California Edison (SCE), utility regulators in California have indicated that they will allow utilities to issue long-term leases on idle land as long as the proposed use makes good business sense. Proof of the business value of the use must be well documented. "I think the commissioners realize that utilities need to take advantage of every opportunity they have to generate revenues," Harpster says. "Utilities need to hold down the bottom line to offer the cheapest kilowatthour they can produce."

SCE is now involved in a major effort to evaluate all its land and water resources for potential use in aquaculture, among other businesses. The buffer land around generating stations is a prime candidate. "The idea is to surround a power station with an apron of industries that are somehow dependent on the plant," says John Palmer, a research project manager in environmental affairs at SCE. "That way, you're making the best use of the available resources." He notes that the available leasable land could total a few hundred acres at a single power station. "We're very excited about it, quite frankly," says Harpster. "We think it'll be good for Edison, good for our ratepayers, and good for our shareholders too."

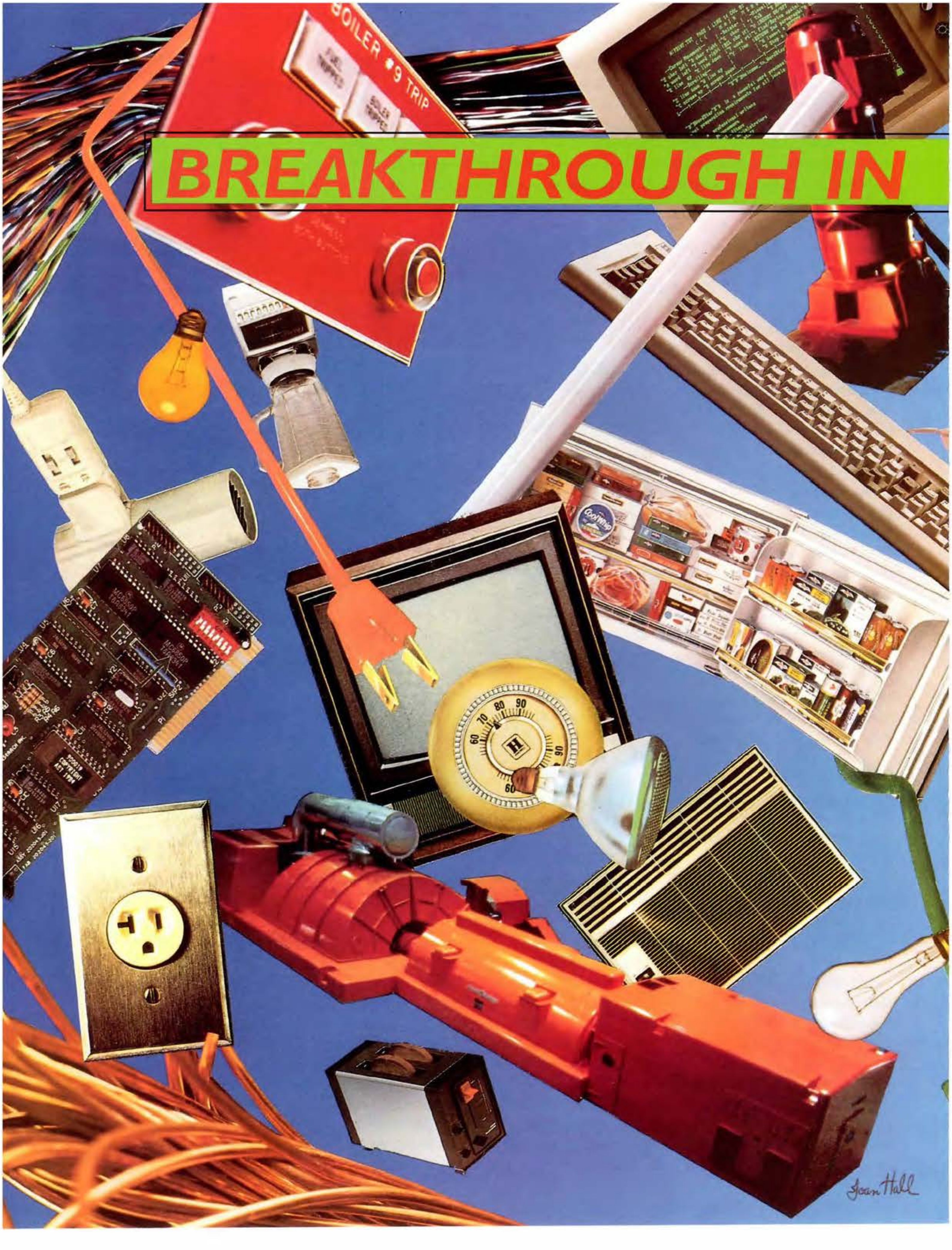
Deregulation is also encouraging other avenues of utility involvement in aquaculture, ranging from investment in and part ownership of fish farms to the direct operation of such facilities. As Berning notes, a company seeking new areas for diversification could even turn an existing fish-restocking program into a moneymaker by selling surplus fish. Says Jones of EPRI, "We're hoping that real-world demonstrations like the one we are planning will help streamline the industry so that aquaculture can live up to its full potential in this country. More aquaculture in the United States means not only more electricity sales for utilities but more jobs for the economy and fewer fish imports. This is an area where utilities can have a great impact." ■



RAINBOW TROUT
(Salmo gairdneri)

Background information for this article was provided by Myron Jones of the Customer Systems Group.

BREAKTHROUGH IN



STABILITY ASSESSMENT

by Paul Haase

THE STORY IN BRIEF **Maintaining a stable flow of electricity is critical for secure power grid operation and customer satisfaction. As utilities increase utilization of their transmission and distribution assets, serious new stability problems are cropping up, problems that can have long-distance impacts not predicted by conventional stability analysis tools. Recently, in exploratory mathematical research at Iowa State University, EPRI-sponsored scientists developed a breakthrough method for enhancing stability analysis to address the new problems. The application of this method, which is based on a 100-year-old mathematical concept known as normal forms, promises to increase power system efficiency by improving utilities' ability to predict and control grid behavior.**

At some time, almost everyone has noticed the lights at home or the office flicker. Perhaps they dimmed for a moment when a coffeepot or an air conditioner in the next room was turned on. Maybe they flickered during a violent storm when, presumably, a power line somewhere blew down. Or possibly it was on a calm evening, for no obvious reason. Whatever the circumstances, the flickering was an indication of power flow fluctuations brought on by changing electrical conditions somewhere, possibly far away, on the power grid.

The huge and the restless

Electrical changes almost anyplace can affect the lights at home or the office because most things electrical, from televisions to transformers, are interconnected by wires and cables. These wires exist in huge, continent-spanning systems composed of regional and utility-centered power grids. Each constituent grid is itself large; that of a typical North American utility includes dozens of generators, hundreds of thousands of miles of cables and wires (including several high-capacity tie-line links to neighboring grids), tens of thousands of automatic control devices, and many millions of outlets. Plugged into these outlets (and thus part of the grid along with the generators, wires, and controllers) are motors, air conditioners, toasters, air compressors, hair dryers, arc furnaces, battery chargers, blenders, computers, freezers, sump pumps—all manner of industrial, commercial, and residential end-use equipment. The activity of these devices affects, and is affected by, the behavior of the whole assembly.

"For a power grid, each event—a light switched on or a line shorted out, for instance—changes the overall electrical and physical characteristics of the entire system," says Dejan Sobajic, a manager for grid operations and planning in EPRI's Power Delivery Group. "With lights and motors and end-use devices going on and off all the time, the electrical state of a grid fluctuates constantly. Utilities work hard to minimize flickering and prevent worse problems."

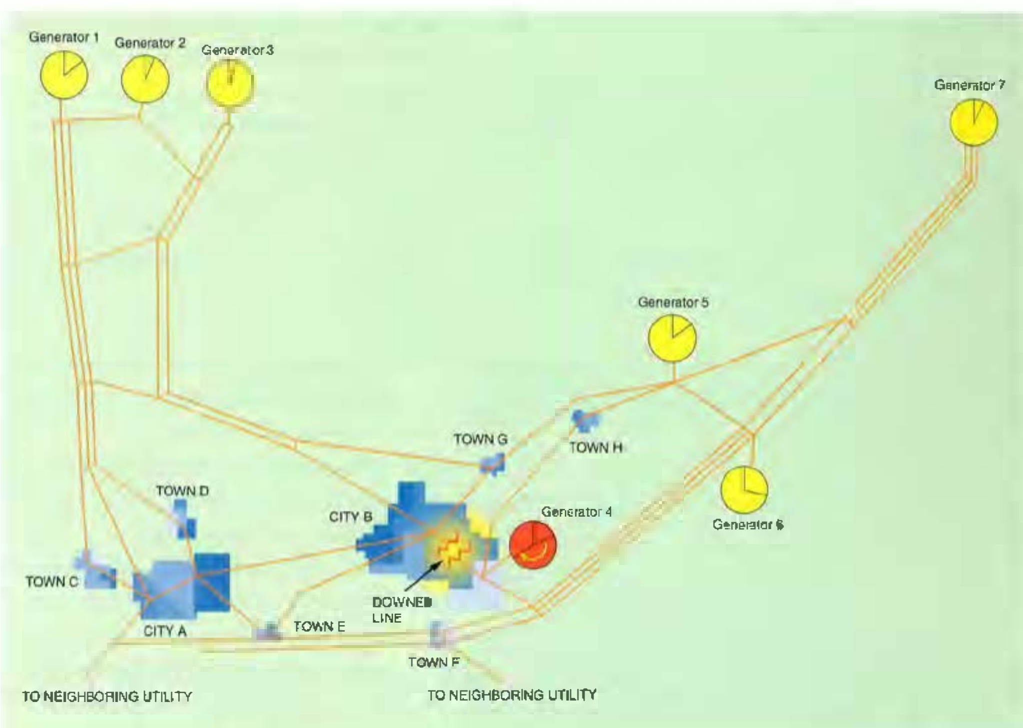
Identifying and controlling the electrical fluctuations that could precipitate outages or other stability problems constitute a stiff challenge. As might be expected, nearly all fluctuations are insignificant: they result only in minute, local power flow disturbances that quickly die out. Some fluctuations are more substantial: they cause large disturbances that must be dampened by automatic controls and compensators to prevent power surges or other problems. And a very few are potentially catastrophic. Under worst-case combinations of conditions, electrical changes can induce highly unstable power fluctuations that feed on themselves, overwhelm local controllers, and cascade unpredictably across the grid. Wild re-

verberations of current or voltage can result, leading to failure of critical components and outages. For secure grid operation, the electrical conditions associated with catastrophic cases must be avoided. Unfortunately, not only is it difficult to know exactly where and how much electricity exists within a large grid, but the physical laws governing the behavior of electricity are also complex. No good conceptual model exists. A common scheme likens the flow of electricity in a power system to that of water in a system of pipes, with current analogous to volume (how much electricity there is) and voltage like pressure (the force "pushing" the electricity around). Thus generators are like pumps, switches are like valves, and end-use equipment is like water-driven machinery. But this basic model fails to address critical aspects of power flow, such as alternating and multiphase current, power electronics switching, and the inability to store electricity. What's more, even the smallest power systems are much more complex and interconnected than any system of pipes. Power engineers thus turn to complicated mathematics that abstractly describe what's going on.

The mathematical models used by utility engineers to understand the state and flow of electricity in a power grid go right to the source: the rotational behavior of the generators that supply the grid with power. These models consist of coupled nonlinear differential and algebraic equations. There is one equation for each generator within a grid; it describes the spinning motion of that machine's rotor and captures its interactions with controls and the network.

The rotation of generators characterizes power levels and power flow dynamics because the electrical state of a power grid and the spinning of its generators are linked—it is of course the generator rotation that provides electricity to the grid in the first place. The linkage goes both ways: the electrical state of a network determines its ability to absorb additional power and thus controls, through varying electromagnetic drag on the generators, how much of the spinning energy in the generators is converted to electricity and how much remains as rotation (see sidebar on page 27).

When a fault causes a short circuit or when something on the power system is turned on or off, the electrical state of the system changes and the speed at which the generators spin increases or slows. Ordinarily, all the generators supplying power to a system spin synchronously (in North America, at 60 cycles per second or some multiple of this rate). However, because of the differing electrical characteristics throughout a power network, generators at different locations may spin some degree out of phase with each other—that is, the "top" of the rotor for one generator may be up when that of another machine is down or at three o'clock. The amount of phase difference between two generators is called the phase angle or angular shift, and it is by measuring the changing relative phase angles of all generators following a disturbance that the associated power flow fluctuations in a system can be revealed.



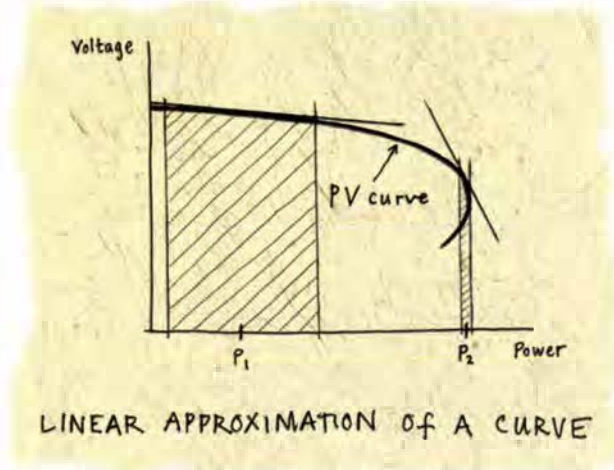
INTERCONNECTION AND STABILITY **Modern electric power systems involve millions of components and complex interconnections. A downed line in city *B* could, in theory, affect lights in any other city or town on the grid—and in most cases via multiple pathways. Utilities characterize electrical stability for these complicated systems by the rotational behavior of the generators powering the grid. Ordinarily generators spin synchronously, with phase differences that depend on local conditions. Instability is indicated when a generator begins spinning faster or slower than the others, shifting its phase (as shown for generator 4).**

SCHEMATIC BY ANTHONY URBAN

Modeling for control and safety

"The way in which generator phase angles vary can be likened to the behavior of an assembly of weights connected by springs," says Sobajic. "Jostle one weight and soon they all wiggle. The overall pattern of oscillation depends on the magnitude and location of the initial disturbance, the mass of the individual weights, and the arrangement and strengths of the springs linking them." Drawing on this concept, utility engineers obtain power flow information from minute changes in the rotational speed of all the generators connected to a grid. Disturbances that require compensation can be identified, as well as ways of controlling them; power flows and combinations of failures that could lead to system instability can be determined. Highly sophisticated computers and mathematical techniques are used for these tasks, and analysis procedures differ.

To identify dampable disturbances and design automatic controls, global knowledge about grid behavior is needed; relations hidden within the behavior of the whole assembly are key. These relations are revealed through analysis of a simplified, linear, model of generator dynamics. (Mathematical techniques do not exist at present for behavioral analysis of the fully detailed, nonlinear, model.) First, individual generator equations are approximated linearly and solved simultaneously; then they are combined into a whole-grid model and analyzed. The linearization, which is based on a technique called Taylor series expansion, is conservative, and controllers designed and sited on the basis of such an analysis provide qualitatively correct regulation of disturbances. For optimal performance, however, they must be fine-tuned in the field.



LINEAR LIMITATIONS Generator and power system relations are fundamentally nonlinear: equations that capture these relations appear as curves when graphed. However, the complex computations necessary for power system analysis cannot be performed on curves by using existing mathematics, and straight-line approximations of the curves are necessary. At traditional, conservative loads (P_1), linear approximation is accurate over a wide range of behavior; at today's often higher loads (P_2), it provides a narrow, incomplete representation.

To avoid problematic and potentially catastrophic power flows, what's important is exact knowledge of safe operating limits and critical contingencies. This information is obtained by simultaneously solving the generator equations for a grid. Additional whole-model analysis is not necessary, and the full, nonlinear, expressions can be used. Although the calculations rely on difficult numerical methods, experience with grid behavior enables knowledgeable engineers to focus effort on a small number of representative and worst-case scenarios. Nevertheless, the process is slow, and a two-stage contingency planning approach is used. Teams of power system planners determine poten-

As the Generators Turn

Generators work on the principle that electricity is created in a wire placed in a moving magnetic field. In these devices, massive magnets are spun within tightly wound coils of wire; the mechanical energy of a generator's revolving magnet is transformed into electric energy—electricity—in the wire. This electricity is drawn off by the demands of equipment connected to the wire elsewhere. Also, electricity has a magnetic field of its own, and the field of the electricity created in the generator coils interacts with the magnetic field of the generator magnet, resulting in a magnetic drag on the rotating magnet that varies with the conversion of mechanical to electric energy.

Because the demand of a power system varies with the conditions throughout that system, the amount of electricity drawn off from the generator fluctuates, and so does the magnetic drag at the generator. For example, if more electricity is supplied to a grid (or part of a grid) than is needed, a charge builds up at the generator and the drag weakens; the rotor speeds up. If demand increases, the drag strengthens and the rotor slows.

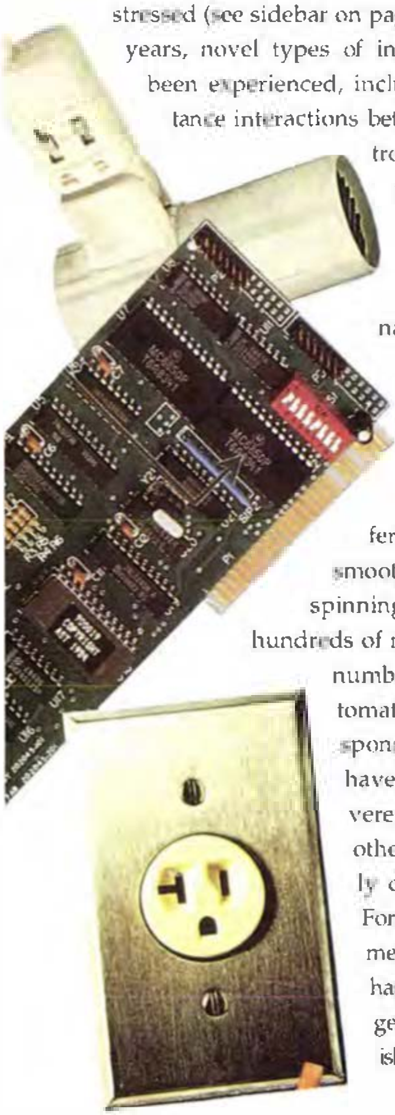
Ordinarily, moment-to-moment rotor fluctuations are small—utilities balance electricity supply and demand over the long term and employ automatic control devices to compensate in the short term. In exceptional cases, however, some of which are related to power system nonlinearity, electrical disturbances can strongly affect a single generator. For the extreme example of a generator completely cut off from the grid by a main bus failure, rotor speed increases very rapidly because all the available energy accumulates as rotation. The machine must be shut down within a fraction of a second to avoid catastrophic failure.

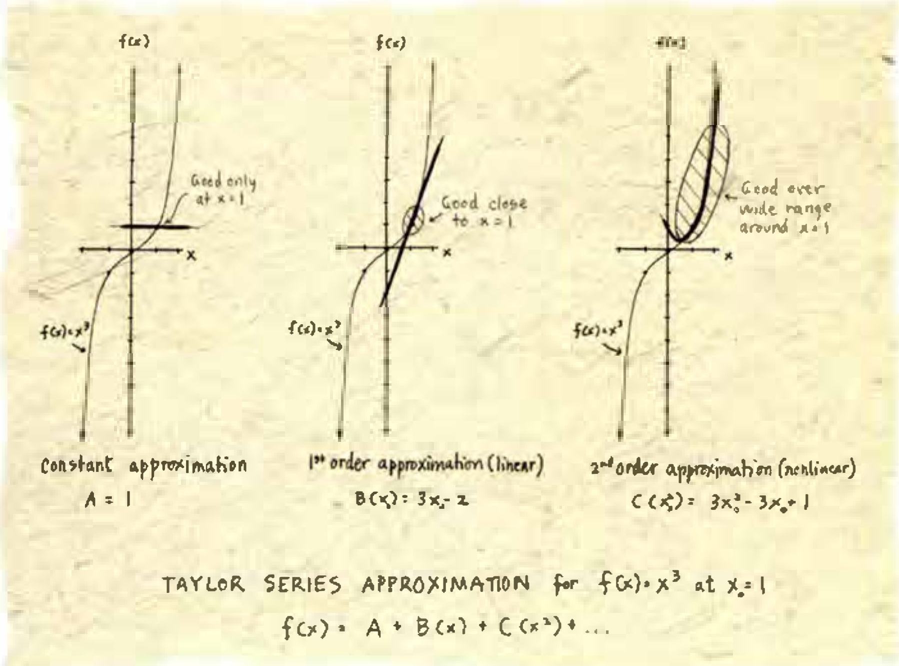
But it is the small fluctuations of rotation that are key to assessing the stability of a power system. The dynamic electrical changes caused by shifting grid configurations overlap and interfere, like ripples made by rain falling on a pond. They reach different generators at different times and affect them differently. By analyzing the varying behavior of the generators simultaneously, the electrical state of the entire grid can be determined. As might be expected, however, the necessary computations are exceptionally complex.

tially dangerous configurations of power flow and disturbances via continuous off-line computation; control room operators use the configuration information, in conjunction with reliability criteria, to determine safe operating limits and make on-line grid adjustments to avoid undesirable contingencies.

"These generator-model methods are utilized by all North American utilities," says Sobajic. "They were developed to handle stability issues arising with rapid growth after the Second World War and have ensured excellent grid security for decades. As a result, all commercial software for designing controllers is based on analysis of linearized grid models, and off-line contingency planning is used everywhere to determine safe operating limits."

With technological change and utility deregulation, power systems are evolving to become more flexible and efficient. At the same time, they are becoming more stressed (see sidebar on page 30). In recent years, novel types of instabilities have been experienced, including long-distance interactions between grid controls and generators. Control devices that generate small electrical signals designed to dampen local disturbances have produced unexpected interferences with the smooth, synchronous spinning of generators hundreds of miles away. In a number of cases, automatic controller responses in one area have resulted in severe disturbances in other, geographically distant, regions. For example, equipment in Arizona has interacted with generators in British Columbia, and fluctuations in Colorado have caused serious disturbances in the San Francisco Bay Area.





TAYLOR SERIES The utility industry approximates generator relations by using the linear terms of Taylor series expansions, which are polynomial-like sums. The first term of a Taylor series is constant, the second is linear, the third is second-order nonlinear, and so on; each term approximates the original equation around a given point, with higher-order terms as corrections. The more terms included, the better the approximation.

A similar new stability problem is interarea separation. For a power grid, separation occurs when one or more generators in a system lose synchronization with the rest. This generator or group of generators speeds up or slows down independently of the rest of the system, creating an electrically separate island of power and load—a small grid of its own. Separation of one or a few local generators following the largest electrical disturbances, such as those caused by catastrophic component failures or natural disasters, is nothing new. This situation is known as plant-mode separation, and utilities have devised control practices that minimize risk and impact on the basis of past experience. (Conventional stability analysis methods do not reveal disturbances for which separation might occur or indicate which generators might be affected.)

By contrast, interarea separation involves loss of synchronization for large numbers of generators, some or all of which can be far from the initial disturbance. This creates many small islands out of one large grid. Some islands will have too much power and others not enough, leading to extreme power flow instabilities and brownouts or blackouts affecting large areas. Several cases of interarea separation have occurred in North America over the past decade. One of the most severe took place during restoration of power in Los Angeles following the 1992 Northridge earthquake; utilities throughout the western United States were affected.

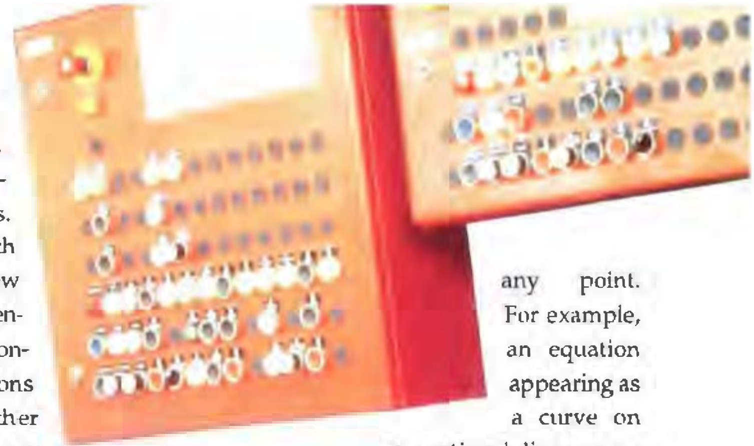
Straight lines and curves

At Iowa State University, EPRI-funded mathematicians and engineers led by Drs. Aziz Fouad and Vijay Vittal suspected that the new instabilities were due to the increasing stress on modern power systems. They reasoned that greater stress increases the importance of nonlinear factors in power flow dynamics, thereby introducing larger unpredictability in the fundamental relations that affect power grids. "The generator equations that govern the behavior of power systems are inherently nonlinear," says Fouad. "As load on power systems increases, it is only natural to see more and more erratic, nonlinear behavior. What's more surprising to me is that we've been able to maintain good grid stability with linear simplification and limited case-by-case contingency analysis for as long as we have."

These approaches have been successful in the past because for linear systems—and for near-linear ones, such as lightly loaded power networks—behavior is described by more or less straight lines; it is regular. A small perturbation produces a small response, and a larger change produces a larger response. Analysis is straightforward (complicated only by the size and interconnectedness of the system), approximation is reliable, and many powerful, well-known mathematical analysis techniques are available.

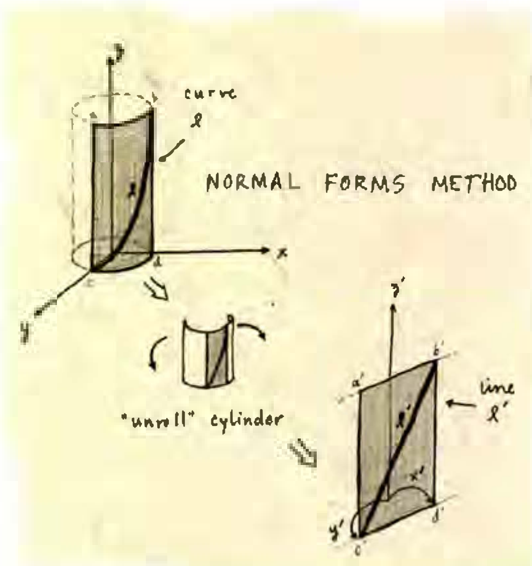
If nonlinearity in a system increases, however, matters become more complex. The behavior of the system becomes described by curved and recurved lines; it is much less predictable. One small perturbation might produce a small response, whereas another, slightly different, small change might produce a very large response. In a stressed—nonlinear—power network, with numerous long-distance interconnections, all kinds of new, irregular behaviors become possible. Conventional scenario-based contingency analysis would not fully reveal safe operating limits because too many unpredictably related cases would have to be computed. And existing linear procedures for designing controllers would not account for the new behaviors at all because by necessity they neglect all nonlinear factors. (Very few mathematical techniques accommodate even simple nonlinear calculations.)

To explore nonlinearity in stressed power systems, advanced means are needed for handling the generator models that describe the behavior of power grids. Fouad, Vittal, and their colleagues took one of two general approaches. They decided to develop more-realistic, but still linear, characterizations for generator equations. Nonlinear factors would be addressed by the improved approximations, which, being linear, could be analyzed via powerful conventional means. (The alternative approach—the development of new mathematical techniques enabling explicit analysis of nonlinear generator equations—is being explored in other EPRI research.) Researchers approached the challenge by applying the method of normal forms to the nonlinear generator equations. Normal forms, developed by the French mathematician Poincaré, is an approximation technique for converting nonlinear equations to linear forms around any point.



With normal forms, the conversion of a nonlinear equation is accomplished by changing the basis of representation around any point. For example, an equation appearing as a curve on conventional linear axes can be made into a straight line if the axes are changed to curves. In the process, the nonlinear equation is divided into two components: the part that can be made linear on the new, curved axes and the residual part that can't. If necessary for more-accurate representation, the normal forms process can be repeated on the nonlinear residual, creating a second set of axes and a new residual; it can then be repeated on that residual, and so on. Because everything but the final residual appears as a straight line, any kind of linear analysis can be performed on the normal forms approximation (individually for each set of axes). Results are recovered by inverting the conversion process at each step, thus changing the answer back to conventional straight-line axes.

For analysis of power system behavior, the normal forms method enables enhanced, nonlinear approximations of generator equations to be expressed in linear form. Consequently, the nonlinear factors included in these equations can be accessed by using conventional linear analysis tools.



NORMAL FORMS TRANSFORMATION
The method of normal forms converts nonlinear relations into linear ones by changing the basis of representation. For example, a curve on the surface of a cylinder can be changed into a straight line by warping its axes in such a way as to "unroll" the cylinder. Linear analysis can be conducted on the straight line and the results recovered by reversing the transformation. This process enables, for the first time, stability analysis based on nonlinear generator relations.

A rounder understanding

To date, Fouad, Vittal, and their colleagues have used the normal forms method to explore the behavior of small but representative power grids—the IEEE 11- and 50-generator systems—with simple nonlinear approximations (second-order Taylor series terms) for the generator equations. This work has demonstrated that interarea instability is indeed associated with nonlinear interaction among generators and controls, even across long geographic distances. Initial studies have shown that nonlinear interactions can sub-

stantially change the behavior of a power system, producing interarea separation as well as other new electrical instabilities. For separation, analysis of the simple nonlinear normal forms representation of a power system can, for the first time, reveal which generators will separate and can provide information on the separation mechanism.

As an initial step toward exploiting the powerful new capabilities made possible by normal forms techniques, researchers have developed systematic procedures to study the behavior of power systems and pinpoint factors critical to instabilities stemming from nonlinearity and stress. Analysis to date indicates that the most important factor contributing to the new instabilities is heavier system loading. It suggests further that second-order Taylor series terms address interarea instability and that third-order terms relate to long-distance control interactions.

The researchers have also developed an index that, for the first time, rapidly predicts the interarea stability or instability of a system for any fault or disturbance. By enabling diverse nonlinear behaviors to be explored fully, this index holds promise for enhancing the security and reliability of stressed power systems. Additionally, the computations are simple enough that analysis can be accomplished by control room operators with ordinary workstations, rather than requiring contingency planners with powerful computers and specialty software.

In light of these promising findings, EPRI plans to integrate the normal forms method into existing analysis software, such as the popular Power System Analysis Package, or PSAPAC. "This software will provide enhanced tools for analyzing system dynamic behavior, including long-distance nonlinear interactions," says EPRI's Sobajic. "The new index, for example, could provide a kind of 'green light/red light' indicator that power system operators will be able to use to assess short-term grid security in near-real time."

Stress in Power Systems

Competitive and environmental pressures, as well as technological advances, are encouraging utilities to operate their power systems differently than in the past. Power wheeling is on the rise, and higher loads are being transmitted across longer distances. New power electronics controls and switches, such as EPRI's FACTS (Flexible AC Transmission System) devices, are being installed on grids to boost performance and efficiency. Throughout the electricity industry, conservatism has given way to cost reduction and maximum utilization of assets.

While these changes enhance efficiency, they also increase stress on power grids. To handle higher loads and more power transfers, transmission and distribution systems are being operated nearer and nearer their limits. Utilities have little practical experience with power grid stability for such conditions, and because the systems are so complex, comprehensive mathematical analysis is as yet unavailable. The analysis that has been done indicates the possibility of chaos in stressed power systems, the most unstable behavior possible. Furthermore, power electronics devices are known to add significant new power flow harmonics for all modes of grid operation, potentially affecting stability at any level of load.

"Maintaining power flow stability in competitive markets has utilities caught between the proverbial rock and hard place," says EPRI's Martin Wildberger, manager for mathematics and information science, Strategic R&D. "Efforts to enhance grid efficiency increase stress and the need for careful control, while deregulation and the division of large, integrated utilities into separate generation, transmission, and distribution companies reduce the ability of any one organization to manage global power flow. Utilities now need more understanding of their systems than ever." □

Additional research continues at Iowa State University. Simple nonlinear approximations of generator equations will be further analyzed to explore the effects of high loadings and power electronics nonlinearities on power grids. Normal forms will also be applied to more-complex nonlinear approximations of generator equations. And these advanced methods will be used to analyze dynamic behavior and separation for an actual power system, that of Manitoba Hydro.

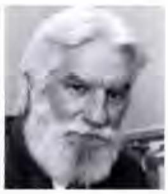
"Our system can be highly stressed," says Doug Chapman, manager of the Manitoba Hydro System Performance Division. "Our major generators, located on the Nelson River, which flows into Hudson Bay, are linked to our customer base in Manitoba by two 900-kilometer-long high-voltage dc transmission lines. Loss of this critical dc backbone could create severe problems for our system, with system breakup a possibility. Normal forms analysis may help us identify key system separation boundaries—and possibly help us design operating procedures, protective measures, or automatic controllers that could ensure the creation of viable, stable islands in the event of a breakup."

According to Sobajic, the normal forms efforts and the other mathematical research sponsored by EPRI can improve the security and efficiency of power systems by developing a deeper understanding of their complex behavior. "The new knowledge afforded by the normal forms method will enable EPRI to create guidelines for designing improved controls that will help stabilize power systems by damping out dangerous oscillations, as well as guidelines for situating these devices on the power system to optimize their effectiveness," says Sobajic. "Eventually, improved understanding should enable on-line control of instability problems like generator separation and, ultimately, active avoidance of instabilities altogether." Lights may never flicker again. ■

Background information for this article was provided by Dejan Sobajic of the Power Delivery Group and Martin Wildberger of Strategic R&D.

CONTRIBUTORS

Technical sources for Journal feature articles



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WILDBERGER

Power Applications for Superconductivity (page 6) was written by Taylor Moore, *Journal* senior feature writer, with principal assistance from two EPRI research managers.

Paul Grant, executive scientist, Strategic R&D, manages programs in superconductivity and wide-band-gap semiconductors. Before joining EPRI in 1993, Grant worked at IBM Corporation for 40 years, much of that time as a scientist at the Almaden Research Center in San Jose, California. He earned a BS degree in electrical engineering at Clarkson University and AM and PhD degrees in applied physics at Harvard University.

Donald Von Dollen, target manager for underground transmission in the Power Delivery Group, joined EPRI in 1991. Before that, he worked three years for Pacific Gas and Electric Company as an engineer in the R&D and technical services programs. Von Dollen earned a BS in physics from California State University, Sacramento. ■

Fish Market Lures Utilities (page 16) was written by Leslie Lamarre, *Journal* senior feature writer, with assistance from **Myron Jones,** manager for environment and energy management in the Customer Systems Group. Before joining EPRI in 1990, Jones was vice president of a subsidiary of Pacific Gas and Electric, where he was responsible for natural gas sales and corporate planning. He has also worked for Bechtel, Shell Development Corporation, United Technologies, and Rust Engineering. Jones holds an MS in chemical engineering from the University of Maine. ■

Breakthrough in Stability Assessment (page 24) was written by science writer Paul Haase with the assistance of two members of EPRI's technical staff.

Dejan Sobajic, manager of power systems control in the Power Delivery Group, came to EPRI in 1993 after five years as engineering manager at AI Ware, Inc., where his responsibilities included coordination of software design and development, strategic planning, and market evaluation. During that time, he also conducted research at Case Western Reserve University on intelligent systems and their use for power system operation and control. Sobajic received bachelor's and master's degrees in electrical engineering from the University of Belgrade, Yugoslavia, and a PhD in systems engineering from Case Western Reserve.

Martin Wildberger of the Strategic R&D staff manages exploratory research in applied mathematics and information science. Additionally, he provides Institute-wide support in mathematical modeling and computer simulation. Before joining EPRI in 1992, Wildberger was chief computer scientist at General Physics Corporation for 11 years. Earlier he served for over 20 years as an officer in the U.S. Navy, specializing in aerospace engineering. He has also held teaching and research positions at Howard University and the University of Maryland. Wildberger received a BS degree from Fordham University, an MS from the U.S. Naval Postgraduate School, and a PhD from the Catholic University of America. ■

Electric Vehicles

School Bus Gets Geared Up in Alabama

Some students in Hoover, Alabama, will be returning to classes this fall in an electric school bus—one of the first to be placed into operation in a U.S. school district. The

vehicle arrived in Hoover, a suburb of Birmingham, in July and is currently being outfitted with data acquisition equipment that will monitor its performance. During the remainder of the summer, operators will be trained to drive the bus.

With assistance from EPRI and Alabama Power Company, the Hoover School District purchased the bus for operation in its permanent fleet, which otherwise consists of diesel-powered buses. Detailed data on the vehicle's performance will be gathered over a two-year period.

The full-size bus, built by Blue Bird Corporation of Macon, Georgia, can carry 72 passengers and can travel about 80 miles between charges. (School buses in the district travel about 40 miles a day, on average.) The vehicle will be regularly charged overnight at the school district's maintenance yard, which has been specially wired for this purpose. As Ed Riddell, EPRI's manager for the project, points out, school buses make an excellent application for electric vehicle technology, since they travel relatively short distances at modest speeds. Also, unlike other types of buses, school buses do not have air conditioning, which consumes a significant amount of battery power. And school buses make frequent stops, during which the battery is not used. In contrast, diesel buses continue to burn energy—and to pollute—while they idle.

Information on the vehicle's performance—including its electricity consumption, mileage range, speed, and acceleration—will be published in an EPRI report.

■ *For more information, contact Ed Riddell, (415) 855-2984.*

Energy Efficiency

New Controller Will Reduce the Cost of Compressed Air

U.S. manufacturers rely on compressed air to power a variety of applications at their industrial plants, from moving materials to running hand tools. At many of these plants, compressed air is the single largest user of electric energy, representing as much as 25% of the entire electricity bill.

Seeking to maintain a competitive edge, many industrial manufacturers are exploring ways to improve the efficiency of their compressed-air systems. The multiple compressors employed at industrial plants are typically controlled by a plant operator, who sets them to provide a certain amount of air pressure at a given time. In many cases, these settings, called operating points, are manually adjusted several times during each shift on the basis of the operator's personal knowledge of the plant's compressed-air requirements.

Automated control of compressed-air systems can significantly increase their efficiency. In a project that got under way this summer at Gould's Pumps—a manufacturer in Seneca Falls, New York—EPRI is funding the demonstration of a sophisticated controller that is expected to result in a 5–10% reduction in the amount of electricity consumed at the plant for producing compressed air. Mechanical and operational improvements being undertaken as part of this project will offer additional savings.

Automated control of compressed-air systems is not a new concept. In fact, some industrial plants have employed such controllers for decades. Aside from determining the best operating points for multiple air compressors in a given plant, automated controllers adjust those settings periodically, according to the demand for air in the plant. The controller being demonstrated in the EPRI project will include some advanced capabilities not available in other controllers. One of these capabilities is enhanced control for loads that come on-line simultaneously. (Traditional methods for handling simultaneous loads involve boosting pressure to avoid sudden pressure drops. However, such pressure boosts typically overcompensate, resulting in wasted energy.)

Controller installation and the mechanical modifications to the compressed-air system at the Gould's plant are expected to be completed this fall. The system will then be monitored for one year. During that time, computer analyses will be conducted to verify and refine the controller's design. Project cosponsors include New York State Electric & Gas Corporation, the New York State Energy Research and Development Authority, and the Empire State Electric Energy Research Corporation.

■ *For more information, contact Larry Carmichael, (415) 855-7982.*

Chilled Aeration

Green Weapon in War Against Grain Pests

Fighting off insects is a running battle for the grain industry in the United States, the world's largest grain producer and exporter. Here, billions of bushels of grain are typically stored for as long as three years before being processed and consumed. Making the task even more challenging, the federal government has banned, as of 2001, the use of the popular pesticide methyl bromide—one of only two fumigants currently permitted for grain.

One option that has emerged as an attractive alternative to pesticide use is the cooling of grain inside storage bins. Since insect life cycles are directly related to temperature, reducing temperatures in these bins to below 55°F can control infestation by such common pests as the grain weevil and the flying moth.

Traditionally, grain handlers have cooled their stockpiles with fans that draw air from outdoors. But this technique is effective only during the winter, when outdoor temperatures are low enough to accomplish the task. Now, chilled-aeration technology is available to U.S. grain handlers, offering year-round, pesticide-free protection for stored grain.

Although chilled-aeration technology has been employed in Europe for some time, it has only recently been adapted for use in the U.S. grain industry. Researchers at Purdue University have improved the efficiency of the European design and developed a commercial-scale system that is now being demonstrated with funding from EPRI and other sponsors. A refrigeration-based air conditioning system, this chilled-aeration unit controls humidity as well as temperature inside grain storage structures like concrete silos and warehouses. The humidity control function prevents mold growth and can enhance grain quality.

With funding from EPRI, Western Resources, and Cinergy, the Purdue researchers have undertaken a series of three demonstrations of their chilled-aeration system. These eight-week demonstrations, which are scheduled for three summer seasons, will indicate how well the system holds up under hot and humid conditions. During the demonstrations, the researchers are closely monitoring grain quality and pest infestation as well as electricity use and system output to determine how the chiller compares with traditional aeration methods. The resulting data will be used to conduct a comprehensive analysis of the system's economic viability.

The first demonstration, conducted last summer at a commercial grain-handling facility in Kokomo, Indiana, indicates that the technology is economically competitive with fumigation: it costs about 1¢ per bushel, compared with 1–2¢ per bushel for fumigation. This summer, the system is being tested at a barley-malting facility in Kansas. An entirely different setting will be selected for next year's demonstration.

Aside from determining the economic viability of chilled aeration, the demonstrations will help introduce the technology to U.S. grain processors and food manufacturers. "The postharvest industry, from the farm gate through the manufacturing and processing of food and feeds, is an important customer of the electric utility industry," says Myron Jones, EPRI's manager for the project. "If these customers adopt chilled-aeration technology, the resulting electricity sales could be significant."

■ *For more information, contact Myron Jones, (415) 855-2993.*

PSE&G Demonstrates SNCR Technology for NO_x Control at Mercer Station

Utilities now have another option for controlling emissions of nitrogen oxides (NO_x) from wet-bottom boilers, thanks to the recent pioneering demonstration of selective noncatalytic reduction (SNCR) technology at unit 2 of Public Service Electric and Gas Company's coal-fired Mercer station. The demonstration was cosponsored by PSE&G and EPRI.

The project confirmed the feasibility of using SNCR in both of Mercer's 321-MW units. Compared with using higher-cost selective catalytic reduction (SCR) technology in one of the boilers, this approach will allow PSE&G to save a projected $128 million over the next 15 years. The Mercer demonstration results will also benefit other utilities with wall- and turbo-fired boilers (boilers having a total generating capacity of about 6900 MW) and cyclone-fired boiler units (23,000 MW), for which SNCR is now a viable NO_x control option.

In 1993, PSE&G was faced with identifying NO_x compliance plans for all its fossil power plants, as were other utilities in the Northeast's Ozone Transport Region. SCR was viewed as a less-than-optimal compliance option because of its high cost, its space requirements, and the need to maintain low ammonia slip and pressure drop. On the other hand, the alternative technology—SNCR—had not been demonstrated for wet-bottom boilers at utility scale, and there was uncertainty about its emissions reduction potential, possible operating problems, and overall cost-effectiveness.

The cosponsored demonstration of Nalco Fuel Tech's NO_xOUT SNCR system with urea injection at Mercer confirmed that a 38% NO_x reduction can be achieved over the entire load range with low ammonia slip (less than 5 ppm) and no adverse impacts on unit operation. The results indicate that SNCR may be adequate to bring some boilers into compliance with the 1990 Clean Air Act Amendments.

For boilers requiring greater NO_x reduction, using SNCR with other control options and with system averaging may be possible approaches. PSE&G demonstrated in subsequent testing at Mercer that SNCR can be combined with In-Duct SCR technology and air heater SCR (in a hybrid SNCR/SCR system) to achieve a 90% NO_x reduction—a level equivalent to that achievable with conventional SCR.

According to James Panacek, site manager at the Mercer station, "SNCR technology has made the Mercer units an integral part of PSE&G's NO_x compliance plans for our immediate needs and into the next century." Adds Eric Svenson, PSE&G's manager of corporate issues, "This project clearly demonstrates that SNCR is a low-cost and effective technology for reducing NO_x emissions and is, in fact, comparable to low-NO_x burner technology on other boiler types." A technical report on the Mercer demonstration (TR-105071) and two assessments of SNCR technology (TR-103885 and TR-102414) are available to members from the EPRI Distribution Center.

■ *For more information, contact Jeff Stallings, (415) 855-2427.*

Leveraging End-Use Data Provides Fast, Lower-Cost Alternative to Metering

Reliable information on commercial customer energy use is essential for many utility applications, including demand-side management planning and evaluation, market planning, product development, and rate design. Until recently, however, there was no proven way to obtain such data other than through costly customer metering. Now utilities can leverage load research information from other utilities to generate reliable end-use data applicable to their own systems.

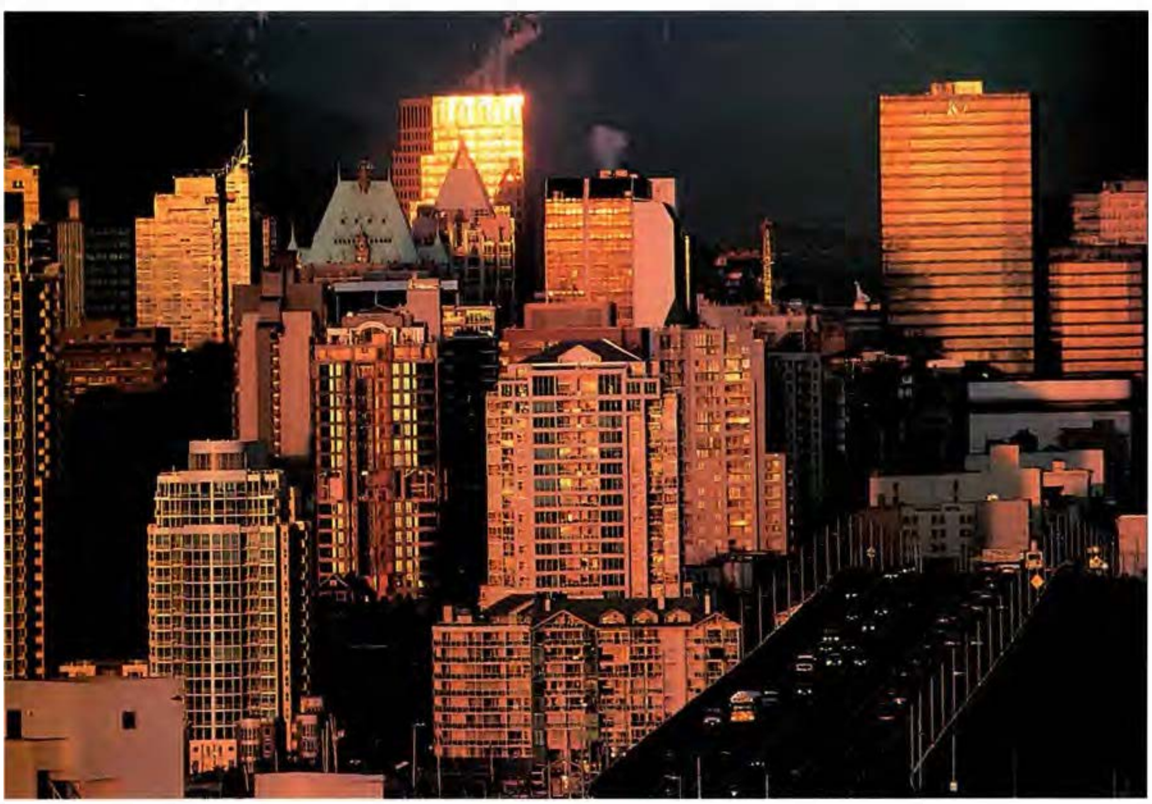
Working in tailored collaboration with the Center for Electric End-Use Data (CEED), which is part of EPRI's Retail Market Tools & Services Business Unit, British Columbia Hydro recently developed a methodology that allows it to transfer end-use metered data from another utility to augment its own small end-use metered sample. This methodology, which uses modeling-derived adaptations, produces end-use data at less expense and in less time than conventional end-use metering, and the data have higher measures of statistical precision than data developed by using prototype building models. In addition, the new methodology can address what-if analyses, provide weather adjustments, and support data transferability between areas and over time.

The data-leveraging methodology allowed BC Hydro to take advantage of existing load research information and to obtain end-use load data for its commercial office segment in about a year's less time than conventional metering strategies would have taken. The Canadian utility estimates that obtaining the same level of data by conventional means would have cost over $1 million.

The resulting data will allow BC Hydro to more quickly fine-tune office-segment product development. In addition, the utility plans to use the data-leveraging methodology to develop end-use load profiles and assess utility products and services for meeting its objective of strategic conservation and sales. Moreover, BC Hydro expects that because of EPRI's involvement, the new methodology will have the credibility needed to persuade other utilities that sharing end-use load data can be mutually beneficial.

"Through a more specific understanding of customer end-use loads, BC Hydro can better match its products and services to the needs of the market," notes Rich Gillman, manager of EPRI's CEED. "EPRI is eager to build on the results of this collaborative effort with BC Hydro to support other utilities. Ultimately, such research may result in a data bank of regionally representative building and technology load shapes." For example, other EPRI data-leveraging projects, recently completed with the Salt River Project and Entergy, have already broadened the experience base. A technical report (TR-105841) on the BC Hydro project is available to members from the EPRI Distribution Center.

■ *For more information, contact Rich Gillman at CEED, (503) 274-4139.*



Magnetic Field Management

Handbooks for Reducing Transmission Line Fields

by Richard Lordan, Environment Group

EPRI is delivering tools, concepts, and guidelines to give utilities options for reducing the magnetic fields associated with overhead transmission lines ranging between 115 and 500 kV. As part of this effort, the Institute has published three engineering handbooks under the title *Magnetic Field Management for Overhead Transmission Lines*. The first handbook (TR-103328), subtitled *A Primer*, brings together in a convenient form much of the material on transmission line magnetic fields developed over the past decade by the technical staff of EPRI's Power Delivery Center at Lenox, Massachusetts (formerly the High-Voltage Transmission Research Center). The primer provides an overview of magnetic field fundamentals and characterizes fields from overhead transmission lines, covering such topics as spatial uniformity, temporal stability, harmonic content, and field orientation in space. One section describes measurement and calculation methods and provides examples illustrating their use.

In addition to commonly used measures of magnetic field exposure (e.g., average and maximum field intensity), the primer discusses other potentially important field exposure characteristics, including cumulative exposure, the frequency of field excursions, and the number of transient or intermittent field events per unit of time.

The handbook compares transmission lines with other field sources—such as residential grounding systems, house wiring, appliances, and distribution lines—highlighting differences in spatial uniformity, time variability, and harmonic content of fields. The magnetic field from a transmission line generally decays in inverse proportion to the square of the distance to the line. Consequently, the field caused by an overhead transmission line is likely to differ by no more than 30% from one point to another in a residence near a transmission line. Within the same residence, in contrast, the fields caused by currents in the grounding system may vary by more than 100 to 1 and fields from electrical appliances by more than 10,000 to 1.

Transmission line magnetic fields vary much less over time than fields from other sources, simply because transmission line loads are by design much more stable than the electrical loads of other sources, such as electrical appliances, house wiring, and power distribution lines. In addition, transmission line magnetic fields are characterized by a relatively pure 60-Hz sinusoidal wave shape, with little harmonic content. Magnetic fields from appliances, fluorescent lighting, distribution lines, and grounding systems of houses have significant harmonic content.

The primer discusses, in some detail, three broad classes of options for managing exposure to magnetic fields from transmission lines: changing activity patterns, shielding, and designing lines to produce lower magnetic fields (Figure 1).

Low-field designs

The second handbook in the series (TR-104413) is subtitled *Potential Options for Low-Field Designs*. On the basis of an evaluation of several new design concepts in light of existing maintenance and construction practices, the handbook recommends several options for reducing transmission line magnetic fields. Tutorial material explains how transmission line design determines magnetic field levels, and the typical levels associated with various line designs are presented. The handbook also presents a method-performance matrix that utility engineers can use to evaluate line configuration performance for lines between 115 and 500 kV. For each field reduction technique, the matrix covers a variety of parameters, including electrical and mechanical characteristics, construc-

ABSTRACT *Public concern about electric and magnetic fields, a concern fueled by scientific controversy and uncertainty over the nature and magnitude of possible health effects, has begun to increase the costs and delay the construction of new power lines and substations. Both the scientific uncertainty and the public concern are likely to persist for some time. In response, utilities have asked EPRI, long recognized as a leader in power delivery system design, to turn its engineering resources to the development of tools and options for managing magnetic fields from power delivery facilities. A series of three engineering handbooks on magnetic field management for overhead transmission lines is the most recent product of this effort. The handbooks cover basic principles, low-field designs, and field cancellation with shielding loops.*

tion and maintenance criteria, costs, configuration, and aesthetics. Three options for field reduction are examined in detail: compaction, splitting of phases, and transposition.

Compaction involves reducing the distances between phases on a transmission line. General compaction reduces distances between the conductors (and the ground wire, if possible) at the towers—and consequently all along the span. This option requires tower reconstruction work and makes live-line maintenance more difficult. Another option, in-span compaction, reduces the distances between conductors in the span without changing the line geometry at the tower; thus clearances for maintenance work on insulators and hardware are not affected. For some existing lines, it may be possible to implement compaction simply by adding in-span spacers. However, in-span compaction is not as effective as general compaction in reducing magnetic fields, and the in-span spacers produce additional locations on the line where mechanical fatigue can take place.

Phase splitting of a three-phase line involves dividing the current on each phase between two or more conductors. From a distance, the magnetic field of these like-phased conductors is similar to that of a single conductor positioned at their geometric midpoint. If the like-phased conductors of all three phases are positioned so that they share a common midpoint, the magnetic field produced by the transmission line behaves, from a distance, as though its source were a single conductor carrying little or no current. In addition to a substantial field reduction, split-phase lines offer the advantage of additional power-carrying capacity. These benefits must be weighed against additional structural support requirements and the costs of additional conductors, insulators, and hardware.

In the field reduction technique called transposition, the relative position of the parallel phase conductors is changed in a helical pattern along the span. Because different short segments of the line produce fields at different angles in space, the total magnetic field (which is the sum of the different components of each segment) is less for transposed lines than for parallel lines. In addition to this helix effect, transposition reduces the phase spacing in the middle of the span, achieving a further reduction of magnetic fields through compaction while maintaining standard clearances at the tower. Transposition has several disadvantages, however. Installing transposed conductors is extremely difficult and time-consuming. Also, it typically is necessary to use in-span insulators to maintain midspan clearances between phases, and these increase costs and subject the conductors to mechanical fatigue. In addition, insulators must be redesigned to accommodate midspan compression loads.

The handbook discusses the use of computer programs, including EPRI's TLWorkstation and EMFWorkstation, to estimate line performance. It also identifies a number of potential technical problems and research needs.

Figure 1 At EPRI's Power Delivery Center, researchers have used test lines to evaluate low-magnetic-field designs for overhead transmission lines. Results from this and other EPRI EMF work have been integrated in a series of comprehensive field management handbooks for utility engineers.

Cancellation loops

Sometimes neither restricting human activity near a transmission line nor modifying the line's design is an attractive option for reducing magnetic field exposure. Especially when the field reduction is targeted at a few spans of line, the preferred option may be to use cancellation loops. Currents circulating in these loops create a magnetic field that has the same direction in space (but opposite phase) as the field from the phase conductors. The cancellation loop field partially cancels the phase conductor field. The third handbook in the series (TR-105571), subtitled *Field Reduction Using Cancellation Loops*, explains the principles of cancellation loop operation and provides the utility engineer with tools to design and construct such systems.

Cancellation loops can be placed either around a work area (subject shielding), in which case the aim is to reduce the field inside the loop, or around a source (source shielding), in which case the aim is to reduce the field outside the loop. The handbook discusses both types of systems. It also discusses both active and passive cancellation loop systems. For transmission line applications, passive systems (in which currents are induced) have received more attention because they do not require the independent power supply and the loop current control of active systems.

The handbook covers all relevant aspects of cancellation loop design, including power supply options and capacitor requirements, safety and grounding, cost evaluation of designs, maintenance requirements, and sensitivity of the magnetic field to changes in cancellation loop parameters.

To help utilities tailor a cancellation loop system to a particular transmission line configuration and field reduction goal, the handbook presents a series of design curves and numerous examples illustrating their use. Various systems are covered. Some use a single two-wire cancellation loop set; others use a single three-wire set; and still others use 2 two-wire sets. Also discussed are mesh systems. The design curves provided cover typical transmission line configurations, such as flat, delta, vertical, double-circuit superbundle, and double-circuit low-reactance lines.

The handbook distills considerable practical experience, including the lessons learned from the design and installation of a number of cancellation systems for buildings and areas near transmission lines. The geometry and design parameters of a cancellation loop system depend on whether the loop is to be optimized to reduce the field at a single location or over a large area, and on whether the maximum field or the average field in the area is to be minimized. Reducing the field everywhere around the transmission line, termed distant field reduction, typically produces a magnetic field profile similar in shape to the original magnetic field but with reduced amplitude. Distant field reduction requires a design quite different from that required to reduce the field in the immediate proximity of the power line. In the latter case, the design engineer may target both sides or only one side of the line.

Customizing solutions

These handbooks provide solid information on common magnetic field management applications, but utilities often confront unique circumstances in which previous engineering experience with field management solutions can be invaluable. In such cases, companies are urged to consider EPRI's tailored collaboration program. The program leverages funding to make the development of a custom solution very cost-effective for the participating companies, while EPRI and the industry benefit from a broader knowledge base and wider applicability of research findings.

New Technical Reports

Requests for copies of reports should be directed to the EPRI Distribution Center, 207 Coggins Drive, P.O. Box 23205, Pleasant Hill, California 94523; (510) 934-4212. EPRI members that fund the business unit issuing a report can receive the report free of charge (or, in the case of bulk orders, for a nominal price). Others should contact the Distribution Center for further information.

Two-page summaries of the reports announced here are available, free of charge, by fax. To receive a summary, call EPRI's Fax on Demand service (800-239-4655) from a touch-tone phone and follow the recorded instructions, using the fax identification number given in the report listing.

CUSTOMER SYSTEMS

The Model Electric Restaurant, Vol. 3: Analysis and Design
CU-6702-V3 Final Report (WO2890-4)
Contractor: Architectural Energy Corp.
Business Unit: Commercial Technologies & Services
EPRI Project Manager: K. Johnson
Fax ID: 25122

Guide to Energy-Efficient Office Equipment, Revision 1
TR-102545-R1 Final Report (RP2890-20)
Contractor: American Council for an Energy-Efficient Economy
Business Unit: Commercial Technologies & Services
EPRI Project Managers: M. Blatt, J. Kesselring
Fax ID: 25505

Chilled-Water Cooling Coils for Cool Storage: Experimental Studies and Mathematical Modeling
TR-102930 Final Report (RP2732-11)
Contractor: Ray W. Herrick Laboratories, Purdue University
Business Unit: Commercial Technologies & Services
EPRI Project Managers: M. Khattar, R. Wendland
Fax ID: 19512

Freeze Concentration of Dairy Products, Phase 2
TR-103204 Final Report (RP2782)
Contractor: Dairy Research Foundation
Business Unit: Industrial & Agricultural Technologies & Services
EPRI Project Manager: A. Amarnath
Fax ID: 25787

Cool Storage Total Building Construction Cost Benefits: An Owner's and Architect's Guide
TR-104521 Final Report (RP3280-16)
Contractor: Dorgan Associates, Inc.
Business Unit: Commercial Technologies & Services
EPRI Project Managers: M. Khattar, R. Wendland
Fax ID: 22237

CLASSIFY-Profiles, Vol. 4: Designing Energy Services for Commercial and Industrial Customers
TR-104567-V4 Final Report (RP4001-3)
Contractor: National Analysts, Inc.
Business Unit: Retail Market Tools & Services
EPRI Project Manager: T. Henneberger
Fax ID: 25212

Laboratory Testing of Clothes Washers
TR-105098 Final Report (RP3872-1)
Contractor: Arthur D. Little, Inc.
Business Unit: Residential Technologies & Services
EPRI Project Managers: R. Gillman, J. Kesselring
Fax ID: 23738

Designing New Utility Programs and Services: Case Studies on the Use of Conjoint Analysis
TR-105778 Final Report (RP3618-1)
Contractor: Research Triangle Institute
Business Unit: Retail Market Tools & Services
EPRI Project Manager: P. Meagher
Fax ID: 24741

Leveraging Limited Data Resources: Developing Commercial End-Use Information (BC Hydro Case Study)
TR-105841 Final Report (WO3819-18)
Contractor: RLW Analytics, Inc.
Business Unit: Retail Market Tools & Services
EPRI Project Manager: R. Gillman
Fax ID: 24837

Performance Measurement: New Visions for a Competitive Electric Utility Environment
TR-105844 Final Report (WO3269-33)
Contractor: Barakat & Chamberlin, Inc.
Business Unit: Retail Market Tools & Services
EPRI Project Manager: R. Gillman
Fax ID: 24843

Performance Impacts: Evaluation Methods for the Nonresidential Sector
TR-105845 Final Report (WO3269)
Contractor: XENERGY, Inc.
Business Unit: Retail Market Tools & Services
EPRI Project Manager: R. Gillman
Fax ID: 24845

Personnel Protection Systems for Electric Vehicle Charging Circuits
TR-105939 Final Report (WO4857-2)
Contractor: Underwriters Laboratories, Inc.
Business Unit: Electric Transportation
EPRI Project Managers: G. Purcell, L. Sandell
Fax ID: 25786

Electric Chiller Handbook
TR-105951 Final Report (RP4880-4)
Contractor: Energy International, Inc.
Business Unit: Commercial Technologies & Services
EPRI Project Manager: W. Krill
Fax ID: 25596

Analysis for a Fast Food Restaurant: Comparison of Three Fuel Choices
TR-105990 Final Report (WO3544-1)
Contractor: Architectural Energy Corp.
Business Unit: Commercial Technologies & Services
EPRI Project Manager: K. Johnson
Fax ID: 25097

Foodservice Equipment Applications Handbook
TR-105991 Final Report (RP3544-1)
Contractor: Architectural Energy Corp.
Business Unit: Commercial Technologies & Services
EPRI Project Manager: K. Johnson
Fax ID: 25099

Heat Transfer Characteristics of Alternate Refrigerants, Vol. 1: Summary
TR-106016-V1 Final Report (RP3412-6424)
Contractor: ENERGEN Consulting, Inc.
Business Unit: Residential Technologies & Services
EPRI Project Manager: S. Kondepudi
Fax ID: 25148

Heat Transfer Characteristics of Alternate Refrigerants, Vol. 2: Condenser Inside Tube
TR-106016-V2 Final Report (RP3412-51)
Contractor: University of Illinois, Urbana-Champaign
Business Unit: Residential Technologies & Services
EPRI Project Manager: S. Kondepudi
Fax ID: 25149

Field Test Prototype Battery Packs at Selected Utilities: Southern California Edison Company
TR-106019 Final Report (RP4882)
Contractor: Southern California Edison Co.
Business Unit: Electric Transportation
EPRI Project Manager: R. Swaroop
Fax ID: 25156

Best Practices in Strategic Market Management: Cases From the Front Lines of Competition
TR-106043 Final Report (WO4853-1)
Contractor: Macro International Inc.
Business Unit: Retail Market Tools & Services
EPRI Project Manager: T. Henneberger
Fax ID: 25195

Persistence Research of DSM Impacts: Methods, Applications, and Selected Findings
TR-106193 Final Report (RP3269-30)
Contractors: Oak Ridge National Laboratory; Synergic Resources Corp.
Business Unit: Retail Market Tools & Services
EPRI Project Manager: P. Meagher
Fax ID: 25450

Environmental Benefits of Electrification and End-Use Efficiency
TR-106196 Final Report (RP3121-12)
Contractor: Regional Economic Research, Inc.
Business Unit: Retail Market Tools & Services
EPRI Project Manager: P. Sioshansi
Fax ID: 25456

Proceedings: 1996 EPRI Conference on Innovative Approaches to Electricity Pricing—Managing the Transition to Market-Based Pricing
TR-106232 Proceedings (RP2343)
Business Units: Retail Market Tools & Services; Power Markets & Resource Management
EPRI Project Managers: P. Sioshansi, C. Smyser
Fax ID: 25514

Market Opportunities in Electric Residential Cooking
TR-106236 Final Report (RP3417-7)
Contractor: QDI Strategies, Inc.
Business Units: Residential Technologies & Services; Retail Market Tools & Services
EPRI Project Managers: W. Krill, T. Henneberger
Fax ID: 25525

Proceedings: Object-Oriented and Distributed Computing Technologies Workshops
TR-106350 Proceedings (RP4895-1, RP4888-1)
Business Unit: Information Systems & Telecommunications
EPRI Project Manager: D. Cain
Fax ID: 25745

ENVIRONMENT

Effects of Flue Gas Desulfurization System Additives on Solid By-Products
TR-102367 Final Report (RP2485-9)
Contractor: Radian Corp.
Business Units: Environmental & Health Sciences; Environmental Control
EPRI Project Managers: J. Goodrich-Mahoney, R. Moser
Fax ID: 7495

Environmental Effects of Supplemental Wood Preservative Treatments of Electric Utility Poles
TR-103299 Final Report (RP3270-1)
Contractor: Environmental Management Services
Business Unit: Environmental & Health Sciences
EPRI Project Manager: J. Goodrich-Mahoney
Fax ID: 20089

Testing EMF for Potential Carcinogenic Activity: A Critical Review of Animal Models
TR-105880 Final Report (RP2965-22)
Contractors: ICF Kaiser Engineers, Inc.; Joyce McCann
Business Unit: Environmental & Health Sciences
EPRI Project Manager: C. Rafferty
Fax ID: 24911

Characterization and Monitoring Before and After Source Removal at a Former Manufactured Gas Plant Disposal Site
TR-105921 Final Report (WO2879-12, -38)
Contractors: META Environmental, Inc.; Atlantic Environmental Services, Inc.
Business Unit: Environmental & Health Sciences
EPRI Project Managers: I. Murarka, A. Quinn
Fax ID: 24977

Handbook for the Assessment and Management of Magnetic Fields Caused by Distribution Lines
TR-106003 Final Report (RP3959-7)
Contractor: Enertech Consultants
Business Unit: Environmental & Health Sciences
EPRI Project Manager: R. Lordan
Fax ID: 25120

An Individual-Based Instream Flow Model for Coexisting Populations of Brown and Rainbow Trout
TR-106258 Interim Report (RP2932-2, RP9046-2, RP9111-1)
Contractor: Lockheed Martin Energy Systems, Inc.
Business Unit: Environmental & Health Sciences
EPRI Project Manager: J. Mattice
Fax ID: 25562

GENERATION

Effects of Flue Gas Desulfurization System Additives on Solid By-Products
TR-102367 (see listing under Environment)

Coal Quality Expert Coal Characterization Studies, Vol. 2: Croweburg and Wyodak Seam Coals
TR-103041-V2 Final Report (RP1400-25)
Contractor: CQ Inc.
Business Unit: Fossil Power Plants
EPRI Project Manager: D. O'Connor
Fax ID: 25818

Circumferential Cracking on the Waterwalls of Supercritical Boilers, Vols. 1 and 2
TR-104442-V1, TR-104442-V2 Final Report (RP1890-8)
Contractor: Battelle Columbus Laboratories
Business Unit: Fossil Power Plants
EPRI Project Manager: B. Dooley
Fax ID: 22130

Standard Equipment Coding for Reporting Gas Turbine Reliability
TR-104758-R1 Final Report (RP2952-5)
Contractor: Strategic Power Systems, Inc.
Business Unit: Gas & New Coal Generation
EPRI Project Manager: R. Frischmuth
Fax ID: 25894

Characterizing the Trace Element Content of Utility Coals
TR-104868 (see listing under Strategic R&D)

Technical Assessment of Advanced Aeroderivative Gas Turbine Power Plants
TR-104957 Final Report (RP2387)
Contractor: Sargent & Lundy
Business Unit: Gas & New Coal Generation
EPRI Project Manager: A. Cohn
Fax ID: 23476

SCR Design and Operational Recommendations: R&D Lessons Learned
TR-105103 Interim Report (RP3004)
Contractor: Radian Corp.
Business Unit: Environmental Control
EPRI Project Manager: K. Zammit
Fax ID: 25677

A Guide to Coal Handling
TR-105110 Final Report (RP1400-20)
Contractor: CQ Inc.
Business Unit: Fossil Power Plants
EPRI Project Manager: D. O'Connor
Fax ID: 23757

Coal Quality Field Test at Watson Unit 4 of Mississippi Power Company
TR-105137 Final Report (RP1400-25)
Contractor: Electric Power Technologies, Inc.
Business Unit: Fossil Power Plants
EPRI Project Managers: D. O'Connor, A. Mehta
Fax ID: 23801

Field Test of Manufactured Gas Plant Remediation Technologies: Thermal Desorption
TR-105145 Final Report (RP3072-4)
Contractor: Remediation Technologies, Inc.
Business Unit: Environmental Control
EPRI Project Manager: G. Maybach
Fax ID: 23820

Field Test of Manufactured Gas Plant Remediation Technologies: Material Removal and Handling
TR-105146 Final Report (RP3072-4)
Contractor: Remediation Technologies, Inc.
Business Unit: Environmental Control
EPRI Project Manager: G. Maybach
Fax ID: 23819

Zebra Mussel Control Using Periodic Chlorine Dioxide Treatments
TR-105202 Final Report (RP3894)
Contractor: Stone & Webster Engineering Corp.
Business Unit: Fossil Power Plants
EPRI Project Manager: J. Tsou
Fax ID: 23925

Steam Treatment of Zebra Mussels
TR-105203 Final Report (RP3894-4)
Contractor: Stone & Webster Engineering Corp.
Business Unit: Fossil Power Plants
EPRI Project Manager: J. Tsou
Fax ID: 23927

Remediation Technologies for Groundwater at Manufactured Gas Plant Sites
TR-105225 Final Report (RP3642-1)
Contractor: Groundwater Technology, Inc.
Business Unit: Environmental Control
EPRI Project Manager: G. Maybach
Fax ID: 23960

Application of Adjustable-Speed Machines in Conventional and Pumped-Storage Hydro Projects
TR-105542 Final Report (RP3577-1)
Contractor: Harza Consulting Engineers and Scientists
Business Unit: Fossil Power Plants
EPRI Project Manager: J. Stein
Fax ID: 24411

Improved Conventional Testing of Power Plant Cables
TR-105581 Final Report (RP2895-3)
Contractors: Ontario Hydro Technologies; AVO International
Business Unit: Fossil Power Plants
EPRI Project Manager: J. Stein
Fax ID: 24466

Using Sulfur From Liquid Redox Processes as an Oxidation Inhibitor in Wet FGD Systems
TR-105610 Final Report (RP9026-2)
Contractor: Radian Corp.
Business Unit: Environmental Control
EPRI Project Manager: R. Rhudy
Fax ID: 24513

BESIE: A First-Stage Evaluator for Biomass Energy Systems
AP-105788 Final Report (RP4062-2)
Contractor: University of Minnesota, Department of Applied Economics
Business Unit: Renewables & Hydro
EPRI Project Manager: J. Turnbull
Fax ID: 25635

Flue Gas Mercury Measurements Methods Evaluation
TR-105851 Final Report (RP3471)
Contractor: Radian Corp.
Business Unit: Environmental Control
EPRI Project Manager: B. Nott
Fax ID: 24860

Environmental Performance Measurement: A Framework for the Utility Industry
TR-106078 Final Report (RP3006-10, RP9030-2)
Contractor: Decision Focus Inc.
Business Unit: Environmental Control
EPRI Project Manager: M. McLearn
Fax ID: 25257

Next-Generation Geothermal Power Plants
TR-106223 Final Report (RP3657-1)
Contractors: C. E. Holt Co.; H. K. McCluer
Business Unit: Renewables & Hydro
EPRI Project Manager: E. Hughes
Fax ID: 26020

Handbook for Display Development
TR-106314 Final Report (RP3499-1)
Contractors: Centerior Energy Corp.; Entor Corp.
Business Unit: Fossil Power Plants
EPRI Project Managers: R. Pflasterer, M. Perakis
Fax ID: 25672

Plant Information Network Specification
TR-106315 Final Report (RP3499-1)
Contractors: Centerior Energy Corp.; Entor Corp.
Business Unit: Fossil Power Plants
EPRI Project Managers: R. Pflasterer, M. Perakis
Fax ID: 25674

NUCLEAR POWER

Radwaste Desk Reference, Vol. 4: Mixed Waste
NP-7386-V4 Final Report (WO3800-6)
Contractors: Roy F. Weston, Inc.; Duke Engineering & Services, Inc.; Right Angle Industries
Business Unit: Nuclear Power
EPRI Project Manager: C. Hornibrook
Fax ID: 24996

Verification and Validation Guidelines for High-Integrity Systems, Vols. 1 (Main Report) and 2 (Appendices)
TR-103916-V1, TR-103916-V2 Final Report (RP3352-1)
Contractor: SoHaR Inc.
Business Unit: Nuclear Power
EPRI Project Managers: J. Naser, S. Bhatt
Fax ID: 21207

License Renewal Industry Reports Summary
TR-104305 Final Report (RP2643-33)
Contractor: Applied Science and Technology
Business Unit: Nuclear Power
EPRI Project Manager: J. Carey
Fax ID: 21924

Development of Process Control Capability Through the Browns Ferry Integrated Computer System Using Reactor Water Cleanup System as an Example
TR-104378 Final Report (RP3351-2)
Contractor: Science Applications International Corp.
Business Unit: Nuclear Power
EPRI Project Manager: J. Naser
Fax ID: 22032

Hydrogen Water Chemistry Effects on BWR Radiation Buildup, Vols. 2–5
TR-104605-V2–V5 Final Report (RP3313-1, -2, -4)
Contractors: AEA Technology; General Electric Nuclear Energy; NWT Corp.; CENTEC XXI
Business Unit: Nuclear Power
EPRI Project Manager: H. Ocken
Fax ID: 24494

Strategic Initiatives for Nuclear Asset Management: A Case Study
TR-104735 Final Report (RP3343-15)
Contractors: Baltimore Gas and Electric Co.; Janus Management Associates, Inc.
Business Unit: Nuclear Power
EPRI Project Manager: J. Carey
Fax ID: 23073

PWR Molar Ratio Control Application Guidelines, Vol. 2: Secondary Chemistry Control
TR-104811-V2 Final Report (RPS520-6)
Contractor: NWT Corp.
Business Unit: Nuclear Power
EPRI Project Manager: P. Millett
Fax ID: 25398

PWR Molar Ratio Control Application Guidelines, Vol. 4: Methods of Determining Effectiveness of MRC
TR-104811-V4 Final Report (RPS520-11)
Contractor: Dominion Engineering, Inc.
Business Unit: Nuclear Power
EPRI Project Manager: P. Millett
Fax ID: 25601

Guidelines to Implement the License Renewal Technical Requirements of 10CFR54 for Integrated Plant Assessments and Time-Limited Aging Analyses
TR-105090 Final Report (RP3075-14, -15)
Contractors: MDC-Ogden Environmental and Energy Services Co., Inc.; Gilbert/Commonwealth, Inc.
Business Unit: Nuclear Power
EPRI Project Manager: J. Carey
Fax ID: 23728

PWR Primary Water Chemistry Guidelines, Revision 3
TR-105714 Final Report (RP2493)
ES-105714 Executive Summary
Business Unit: Nuclear Power
EPRI Project Manager: C. Wood
Fax ID: 24654

An Analysis of Loss of Decay Heat Removal Trends (1989–1994): Outage Risk Assessment and Management (ORAM) Technology
TR-105802 Final Report (RP3896-2, RP3333-10)
Contractor: Safety Management Services, Inc.
Business Unit: Nuclear Power
EPRI Project Manager: P. Kalra
Fax ID: 24781

Zero Plastics and the Radiologically Protected Area Low-Level-Waste Lockout Program
TR-105834 Final Report (WO2414)
Contractor: Right Angle Industries
Business Unit: Nuclear Power
EPRI Project Manager: C. Hornibrook
Fax ID: 24827

Guidelines for Preparing Risk-Based Technical Specifications Change Request Submittals
TR-105867 Final Report (RP3477-2)
Contractors: PLG, Inc.; Yankee Atomic Electric Co.
Business Unit: Nuclear Power
EPRI Project Manager: F. Rahn
Fax ID: 24888

Risk-Based In-Service Testing Pilot Project

TR-105869 Final Report (RP3719-3)
Contractor Wesley Corp
Business Unit Nuclear Power
EPRI Project Manager F Rahn
Fax ID 24894

Risk-Based In-Service Testing Program for Comanche Peak Steam Electric Station

TR-105870 Final Report (RP3719-2)
Contractor Science Applications International Corp
Business Unit Nuclear Power
EPRI Project Manager F Rahn
Fax ID 24895

Assessment of a Low-Level-Waste Outside Storage Pad Design Method

TR-105891 Final Report (WO3801-1)
Contractor CENTEC XXI
Business Unit Nuclear Power
EPRI Project Manager C Hornbrook
Fax ID 24930

Spent-Resin Disposition: Available Alternatives and Selection Analysis

TR-105901 Final Report (WO2414)
Contractor CENTEC XXI
Business Unit Nuclear Power
EPRI Project Manager C Hornbrook
Fax ID 24944

Vitrification of Low-Level Radioactive Waste

TR-105912 Final Report (WO3500-29)
Contractor VECTRA Technologies, Inc
Business Unit Nuclear Power
EPRI Project Manager C Wood
Fax ID 24962

PWR Steam Generator Sleeving Assessment Document

TR-105960 Final Report (WO3580-6)
Contractors Steam Generator Sleeving Review Committee, Energy Management Services, Inc
Business Unit Nuclear Power
EPRI Project Manager A McIlree
Fax ID 25054

Development of an On-Line Corrosion Product Analyzer

TR-105973 Final Report (RP3388-9)
Contractor GE Nuclear Energy
Business Unit Nuclear Power
EPRI Project Manager P Millett
Fax ID 25073

High-Temperature pH Measurements Using Novel pH Electrodes

TR-105974 Final Report (RPS407-27, RPS522-4)
Contractor Pennsylvania State University
Business Unit Nuclear Power
EPRI Project Manager P Millett
Fax ID 25072

Proceedings: 1995 EPRI Circumferential Cracking Workshop

TR-105983 Proceedings (RPS510-9)
Contractor Dominion Engineering, Inc
Business Unit Nuclear Power
EPRI Project Manager A McIlree
Fax ID 25085

Template for the Submission of Revised Risk-Based Technical Specifications

TR-105987 Final Report (WO3477-11)
Contractor ABB Combustion Engineering Nuclear Operations
Business Unit Nuclear Power
EPRI Project Manager F Rahn
Fax ID 25090

Results and Analyses of Irradiation/Anneal Experiments Conducted on Yankee Rowe Reactor Pressure Vessel Surrogate Materials (Yankee Atomic Electric Company Test Reactor Program)

TR-106001 Final Report (WO4075-1)
Contractor Yankee Atomic Electric Co
Business Unit Nuclear Power
EPRI Project Manager R Carter
Fax ID 25115

Post-Irradiation Evaluation of BWR Fuel From Hatch-1 Reactor

TR-106036 Final Report (WO3564-1)
Contractor GE Nuclear Energy
Business Unit Nuclear Power
EPRI Project Manager S Yagnik
Fax ID 25196

Characterization of PWR Steam Generator Deposits

TR-106048 Final Report (RPS523-1)
Contractor Dominion Engineering, Inc
Business Unit Nuclear Power
EPRI Project Manager R Thomas
Fax ID 25408

A Review of the Economic Potential of Plutonium in Spent Nuclear Fuel

TR-106072 Final Report (RP4200)
Business Unit Nuclear Power
EPRI Project Manager E Rodwell
Fax ID 26093

Proceedings: Vitrification of Low-Level Waste—The Process and Potential

TR-106079 Proceedings (RP2414-75)
Contractor CENTEC XXI
Business Unit Nuclear Power
EPRI Project Manager C Hornbrook
Fax ID 25259

Shoreham Decommissioning: Project Summary and Lessons Learned

TR-106148 Final Report (RP3171-3)
Contractor Long Island Power Authority
Business Unit Nuclear Power
EPRI Project Manager C Hornbrook
Fax ID 25383

Losses of Off-Site Power at U.S. Nuclear Power Plants—Through 1995

TR-106306 Final Report (WO4114)
Business Unit Nuclear Power
EPRI Project Manager A Singh
Fax ID 25661

POWER DELIVERY

West Coast Utility Transmission Benefits of Superconducting Magnetic Energy Storage

TR-104803 Final Report (RP2572-13)
Contractor Battelle Northwest
Business Unit Substations, System Operations & Storage
EPRI Project Manager S Eckroad
Fax ID 23188

Investing Resources to Create Value: The Portfolio Approach to Capital and O&M Budgeting

TR-104917 Final Report (WO3678)
Contractor Strategic Decisions Group
Business Unit Power Markets & Resource Management
EPRI Project Manager R Goldberg
Fax ID 26021

Modeling of Single-Phase Induction Motor Loads in Power System Studies

TR-105341 Final Report (WO2447-6)
Contractor Clarkson University
Business Unit Substations, System Operations & Storage
EPRI Project Manager P Hirsch
Fax ID 24134

Thermal Models for Real-Time Monitoring of Transmission Circuits

TR-105421 Final Report (RP3022-7)
Contractors Power Technologies, Inc , Georgia Power Research Center, Georgia Institute of Technology, Underground Systems, Inc
Business Unit Substations, System Operations & Storage
EPRI Project Manager A Edris
Fax ID 24251

Engineering Handbook for Dispersed Energy Systems on Utility Distribution Systems

TR-105589 Final Report (RP4524-1)
Contractor Electrotek Concepts, Inc
Business Unit Distribution
EPRI Project Manager D Richardson
Fax ID 24477

Study of PWM AC-AC Converters for Custom Power

TR-105601 Final Report (RP3389-17)
Contractor Montana State University
Business Unit Distribution
EPRI Project Manager A Sundaram
Fax ID 24490

Guidelines for the Design and Installation of Transmission and Distribution Cables Using Guided Drilling Systems

TR-105850 Final Report (RP7925-1)
Contractors Sargent & Lundy, Jason Consultants International, Inc , Power Delivery Consultants, Inc
Business Unit Transmission
EPRI Project Manager T Rodenbaugh
Fax ID 24858

EPRI Spill Outline Monitor for PCB and Other Spills

TR-105866 Final Report (RP2028-20)
Contractor Battelle
Business Unit Substations, System Operations & Storage
EPRI Project Manager J Melcher
Fax ID 24886

Standard Test Cases for Dynamic Security Assessment

TR-105885 Final Report (RP3103-2, 3)
Contractors ABB Systems Control Co , Inc , Siemens Energy & Automation Inc
Business Unit Substations, System Operations & Storage
EPRI Project Manager P Hirsch
Fax ID 24920

Analytical Methods for DSA Contingency Selection and Ranking: User's Manual for DIRECT, Version 4.0
TR-105886 Final Report (RP3103-3)
Contractor: Siemens Energy & Automation Inc. Empros Power Systems Control Division
Business Unit: Substations, System Operations & Storage
EPRI Project Manager: P. Hirsch
Fax ID: 24922

Improved Dynamic Equivalencing Software
TR-105919 Final Report (RP2447-2)
Contractor: GE Electrical Distribution and Control
Business Unit: Substations, System Operations & Storage
EPRI Project Manager: P. Hirsch
Fax ID: 24973

Utility Software Operation on Parallel Computers
TR-105920 Final Report (RP3103-6)
Contractor: University of Maryland
Business Unit: Substations, System Operations & Storage
EPRI Project Manager: P. Hirsch
Fax ID: 24975

Strategic Market Assessment of Distributed Resources
TR-106055 Final Report (RP3733)
Contractors: Applied Decision Analysis, Inc.; Brattle/IRI; Distributed Utility Associates; Econix
Business Unit: Power Markets & Resource Management
EPRI Project Manager: C. Smyser
Fax ID: 25216

Impact of FACTS on System Operation and Energy Management Systems
TR-106070 Final Report (RP3832-5)
Contractor: ECC, Inc.
Business Unit: Substations, System Operations & Storage
EPRI Project Manager: A. Vojdani
Fax ID: 25243

Outage Cost Estimation Guidebook
TR-106082 Final Report (RP2878-4)
Contractor: Freeman, Sullivan & Co.
Business Unit: Substations, System Operations & Storage
EPRI Project Manager: A. Vojdani
Fax ID: 25268

Pricing Competitive Electricity Services: Principles and Segmentation Techniques
TR-106215 Final Report (RP7802-3)
Contractors: Christensen Associates; Applied Decision Analysis, Inc.
Business Unit: Power Markets & Resource Management
EPRI Project Manager: C. Smyser
Fax ID: 25488

From Regulation to Competition: Managing the Corporate Portfolio for Maximum Value Creation
TR-106216 Final Report (WO3678)
Contractor: Strategic Decisions Group
Business Unit: Power Markets & Resource Management
EPRI Project Manager: R. Goldberg
Fax ID: 25490

Proceedings: 1996 EPRI Conference on Innovative Approaches to Electricity Pricing—Managing the Transition to Market-Based Pricing
TR-106232 (see listing under Customer Systems)

Distributed Utility Penetration Study
TR-106265 Final Report (RP3733-3)
Contractor: Energy and Environmental Economics
Business Unit: Power Markets & Resource Management
EPRI Project Managers: J. Bloom, S. Chapel
Fax ID: 25578

STRATEGIC R&D

Characterizing the Trace Element Content of Utility Coals
TR-104868 Final Report (RP3440-3)
Contractor: Energy Ventures Analysis, Inc.
Business Units: Strategic R&D; Environmental Control
EPRI Project Managers: J. Platt, B. Toole-O'Neil
Fax ID: 23310

Use of a High-Pressure Roll Mill Hybrid System for Fine Coal Grinding
TR-105384 Final Report (RP8013-12)
Contractor: University of California, Berkeley, Department of Material Science and Mineral Engineering
Business Unit: Strategic R&D
EPRI Project Managers: D. O'Connor, S. Alpert
Fax ID: 24200

Development of Neural Network Controllers for Power Industry Applications, Vols. 1 and 2
TR-105533-V1, TR-105533-V2 Final Report (RP8010-13)
Contractor: Stanford University
Business Unit: Strategic R&D
EPRI Project Manager: J. Maulbetsch
Fax ID: 25676

Nonintrusive Appliance Load Monitoring With Finite-State Appliance Models
TR-105583 Final Report (RP8000-32)
Contractor: Columbia University, Department of Electrical Engineering
Business Unit: Strategic R&D
EPRI Project Manager: L. Carmichael
Fax ID: 24470

High-Temperature Stability of Novel Polyimides
TR-105793 Final Report (RP8007-13)
Contractor: Massachusetts Institute of Technology
Business Unit: Strategic R&D
EPRI Project Manager: B. Bernstein
Fax ID: 24764

Genetic Algorithm Testbed for Expert System Testing
TR-106004 Final Report (RP8015-5)
Contractor: DHR Technologies, Inc.
Business Unit: Strategic R&D
EPRI Project Manager: M. Wildberger
Fax ID: 25124

New Computer Software

Orders for EPRI-developed software should be directed to the Electric Power Software Center, 11025 North Torrey Pines Road, La Jolla, California 92037; (800) 763-3772. EPRI members can receive, free of charge, software developed by the business units to which they subscribe. Others should contact EPRI's Licensing Office at (415) 855-2974.

INFORM: Industrial End-Use Forecasting Model
Version 1.3 (PC-DOS)
Contractor: Regional Economic Research, Inc.
Business Unit: Retail Market Tools & Services
EPRI Project Manager: Paul Meagher

LPDW™: Lightning Protection Design Workstation
Version 3.0 (PC-DOS)
Contractor: Distributed Energy System
Business Unit: Distribution
EPRI Project Manager: Ralph Bernstein

PCTRANS
Version 1.1 (PC-DOS)
Contractor: HydroGeologic Inc.
Business Unit: Environmental & Health Sciences
EPRI Project Manager: Dave McIntosh

Profit Manager
Version 3.08 (Windows 3.1)
Contractor: EPS Solutions
Business Unit: Retail Market Tools & Services
EPRI Project Manager: Perry Sioshansi

ProForma
Version 3.0 (Windows)
Contractor: Science Applications International Corp.
Business Unit: Retail Market Tools & Services
EPRI Project Manager: Perry Sioshansi

RateManager
Version 3.0 (PC-DOS)
Contractor: EPS Solutions
Business Unit: Retail Market Tools & Services
EPRI Project Manager: Perry Sioshansi

RCM (Reliability-Centered Maintenance) Technical Reference for Substations
Version 1.0 (Windows)
Contractor: Halliburton NUS Corp.
Business Units: Substations, System Operations & Storage; Transmission; Distribution
EPRI Project Manager: Predrag Vujovic

RCM Workstation for Substations
Version 1.0 (Windows)
Contractor: Halliburton NUS Corp.
Business Units: Substations, System Operations & Storage; Transmission; Distribution
EPRI Project Manager: Predrag Vujovic

RISKMIN
Version 7.32 (PC-DOS/Windows; RS6000-AIX)
Contractor: Stone & Webster
Business Unit: Substations, System Operations & Storage
EPRI Project Manager: Ram Adapa

EPRI Events

SEPTEMBER

3–4
Nuclear Plant Performance Improvement
Asheville, North Carolina
Contact: Susan Otto, (704) 547-6072

4–6
P²EP (Plant Performance Enhancement Program) Annual Meeting
Asheville, North Carolina
Contact: Susan Otto, (704) 547-6072

10–11
Application of Motors and Drives
Pittsburgh, Pennsylvania
Contact: Carrie Koeturius, (510) 525-1205

10–13
1996 EPRIweb Conference
Atlanta, Georgia
Contact: Michele Samoulides, (415) 855-2127

11–13
Main Feedwater Pump Workshop
St. Petersburg, Florida
Contact: Linda Suddreth, (704) 547-6141

11–13
Turbine Generator Troubleshooting Short Course
Eddystone, Pennsylvania
Contact: John Niemkiewicz, (800) 745-9982

11–13
Underground Transmission Lines: Technical Review
Baltimore, Maryland
Contact: Kathleen Lyons, (415) 855-2656

12
Application of Motors and Drives
Columbus, Ohio
Contact: Carrie Koeturius, (510) 525-1205

12–13
3d Annual Symposium on Electric Power for Compression
Houston, Texas
Contact: Dick Schmeal, (713) 963-9307

15–22
Transmission and Distribution Conference and Expo
Los Angeles, California
Contact: Andrea Duerr, (415) 855-2640

17–20
Steam Turbine Perpformance Monitoring
Eddystone, Pennsylvania
Contact: Jeanne Harris, (800) 745-9982

19–20
Lightning Protection Design Workstation Workshop and Seminar
Raleigh, North Carolina
Contact: Ralph Bernstein, (415) 855-2023

19–20
Remediation of Contaminated Sites
Chicago, Illinois
Contact: Ishwar Murarka, (415) 855-2150

19–20
Wood Pole Workshop
Los Angeles, California
Contact: Bruce Bernstein, (202) 293-7511

22–25
7th International Symposium on Interaction Between Sediments and Water
Baveno, Italy
Contact: Bob Brocksen, (415) 855-7961

24
Efficiency Improvements in Process Systems Using Adjustable-Speed Drives
Cleveland, Ohio
Contact: Carrie Koeturius, (510) 525-1205

24–25
Motor Rewind Seminar
Atlanta, Georgia
Contact: Denise Wesalainen, (415) 855-2259

24–25
Operational Reactor Safety Engineering and Review Group
San Antonio, Texas
Contact: Susan Bisetti, (415) 855-7919

24–26
Machinery Balancing
Eddystone, Pennsylvania
Contact: John Niemkiewicz, (800) 745-9982

24–27
Transformer Performance, Monitoring, and Diagnostics
Long Beach, California
Contact: John Niemkiewicz, (800) 745-9982

25–27
International Workshop on Main Coolant Pumps
Pittsburgh, Pennsylvania
Contact: Susan Otto, (704) 547-6072

26
Efficiency Improvements in Process Systems Using Adjustable-Speed Drives
Plainfield, Indiana
Contact: Carrie Koeturius, (510) 525-1205

30–October 1
Power Quality Marketing Workshop
Knoxville, Tennessee
Contact: Karen Forsten, (423) 974-8288

30–October 2
IRP-Manager Software Training
Minneapolis, Minnesota
Contact: Nancy Bubb, (612) 473-1303

OCTOBER

1
Application of Motors and Drives
St. Louis, Missouri
Contact: Carrie Koeturius, (510) 525-1205

1–2
DSManager Software Training
Minneapolis, Minnesota
Contact: Nancy Bubb, (612) 473-1303

1–2
Profit Manager Software Training
Minneapolis, Minnesota
Contact: Nancy Bubb, (612) 473-1303

1–2
REEPS Software Training
San Diego, California
Contact: Paige Schaefer, (800) 398-0081

1–3
Risk Management for Competitive Markets
Baltimore, Maryland
Contact: Susan Marsland, (415) 855-2946

1–4
1996 Gasification Technologies Conference
San Francisco, California
Contact: Michele Samoulides, (415) 855-2127

2
RateManager Software Training
Minneapolis, Minnesota
Contact: Nancy Bubb, (612) 473-1303

2–4
Magnetic Field Management Seminar
Lenox, Massachusetts
Contact: Leeka Kheifets, (415) 855-8976

3–4
Application of Motors and Drives
Omaha, Nebraska
Contact: Carrie Koeturius, (510) 525-1205

3–4
COMMEND Software Training
San Diego, California
Contact: Paige Schaefer, (800) 398-0081

3–4
Decision Analysis for Environmental Risk Management
Palo Alto, California
Contact: Robert Goldstein, (415) 855-2593

3–4
Users Group Meeting: DSManager, IRP-Manager, ProfitManager, RateManager
Minneapolis, Minnesota
Contact: Nancy Bubb, (612) 473-1303

7–8
INFORM Software Training
San Diego, California
Contact: Paige Schaefer, (800) 398-0081

7–10
Hydrogenerator Maintenance
Seattle, Washington
Contact: Denise Wesalainen, (415) 855-2259

8
Efficiency Improvements in Process Systems Using Adjustable-Speed Drives
Detroit, Michigan
Contact: Carrie Koeturius, (510) 525-1205

9
Life-Cycle Cost Management System Software Training Workshop
Mountain View, California
Contact: Mary McLearn, (415) 855-2487

9
PISCES Database Forum
Irving, Texas
Contact: Lynn Stone, (214) 556-6529

9–10
Advanced Market-Based Products for Electricity Pricing
Atlanta, Georgia
Contact: Connie Smyser, (415) 855-2396

9–10
Interconnected Operations Services Workshop
San Diego, California
Contact: Denise Wesalainen, (415) 855-2259

9–11
Center for Metals Fabrication Electrotechnology Seminar
Dallas, Texas
Contact: Eileen Mauro, (614) 421-3440

10
Efficiency Improvements in Process Systems Using Adjustable-Speed Drives
Tulsa, Oklahoma
Contact: Carrie Koeturius, (510) 525-1205

10–11
PISCES Model Training
Irving, Texas
Contact: Lynn Stone, (214) 556-6529

14–16
Managing Fossil Generating Assets in the Marketplace
Washington, D.C.
Contact: Lori Adams, (415) 855-8763

14–16
Power Quality Interest Group Meeting
Cleveland, Ohio
Contact: Karen Forsten, (423) 974-8288

15–16
Using EPRI Land and Water Models
Dallas, Texas
Contact: Ishwar Murarka, (415) 855-2150

16–18
Tutorial: Preserving Equipment Qualification
Charlotte, North Carolina
Contact: Susan Otto, (704) 547-6072

17–18
EPRI Partnership for Industrial Competitiveness (EPIC)
Newport Beach, California
Contact: Bill Smith, (415) 855-2415

17–18
HELM Software Training
Dallas, Texas
Contact: Paige Schaefer, (800) 398-0081

17–18
Strategic Asset Management for a Competitive Utility Environment
San Diego, California
Contact: Susan Marsland, (415) 855-2946

21–24
Decision Analysis for Utility Planning and Management
San Diego, California
Contact: Charlie Clark, (415) 855-2994

23–25
Achieving Success in Evolving Electricity Markets
Indianapolis, Indiana
Contact: Michele Samoulides, (415) 855-2127

23–25
Fuel Supply Seminar
Denver, Colorado
Contact: Susan Bisetti, (415) 855-7919

23–25
Healthcare Initiative Conference
New York, New York
Contact: Anne Kovalski, (718) 920-0849

24–25
HOTCALC Software Training
Irving, Texas
Contact: Lynn Stone, (214) 556-6529

NOVEMBER

3–6
Insulated Conductors
St. Petersburg, Florida
Contact: Jon Ferguson, (817) 234-8216

6–8
Distributed Resources, 1996
Vancouver, Canada
Contact: Lori Adams, (415) 855-8763

12
Application of Motors and Drives
Seattle, Washington
Contact: Carrie Koeturius, (510) 525-1205

12
Efficiency Improvements in Process Systems Using Adjustable-Speed Drives
San Diego, California
Contact: Carrie Koeturius, (510) 525-1205

12–13
Maintenance-Free Load Tap Changing: Phase 1
Tampa, Florida
Contact: Susan Bisetti, (415) 855-7919

12–14
Valve Packing: Application, Configuration, Engineering, and Program Development
Eddystone, Pennsylvania
Contact: John Niemkiewicz, (800) 745-9982

13–15
Lubrication Oil Analysis
Long Beach, California
Contact: Jeanne Harris, (800) 745-9982

14
Efficiency Improvements in Process Systems Using Adjustable-Speed Drives
Portland, Oregon
Contact: Carrie Koeturius, (510) 525-1205

14–15
Application of Motors and Drives
Los Angeles, California
Contact: Carrie Koeturius, (510) 525-1205

14–15
Electromagnetic Interference Qualification of Digital Equipment
Charlotte, North Carolina
Contact: Susan Otto, (704) 547-6072

14–15
1996 Heat Pump Allies Conference
Annapolis, Maryland
Contact: Michele Samoulides, (415) 855-2127

17–21
Research on Biological Effects of Electric and Magnetic Fields
San Antonio, Texas
Contact: Charles Rafferty, (415) 855-8908

18–20
Maintaining the Integrity of Water-Cooled Generator Stator Winding
Tampa, Florida
Contact: Denise Wesalainen, (415) 855-2259

20–22
Water-Heating Electrotechnologies and WATSIM Software Training
Irving, Texas
Contact: Lynn Stone, (214) 556-6529

DECEMBER

2–3
Power Electronics Applications Center Marketing Workshop
Knoxville, Tennessee
Contact: Karen Forsten, (423) 974-8288

2–4
Power Quality Technical Training
Knoxville, Tennessee
Contact: Karen Forsten, (423) 974-8288

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