Conductive Polymers

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ELECTRIC POWER RESEARCH INSTITUTE

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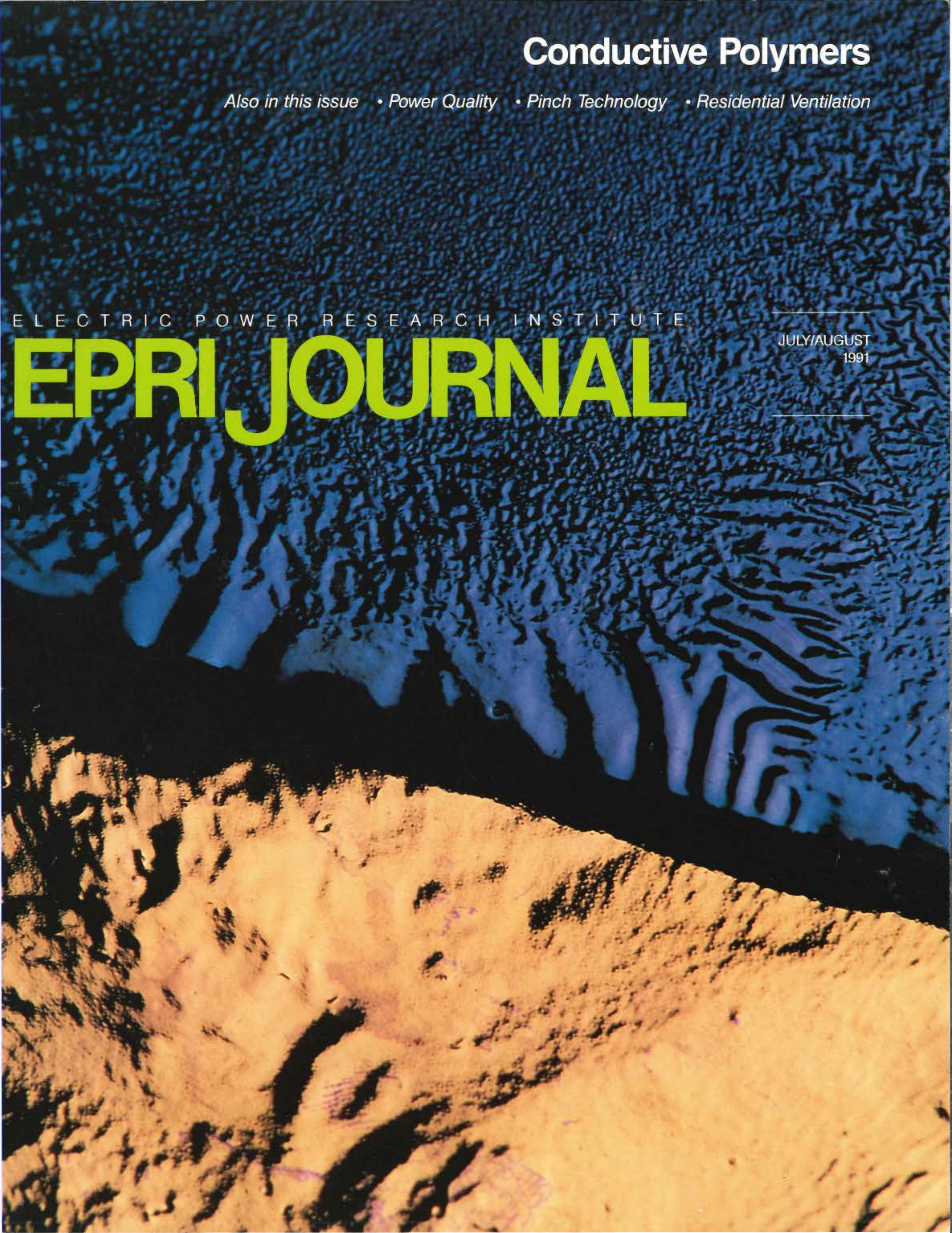

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Cover: Contrasting colors and textures mark the transformation of polyaniline into a conductive polymer in the laboratory of Professor Alan MacDiarmid at the University of Pennsylvania. Chemical doping changes the material from a nonconductive, golden foil into a conductive, blue film. Photo by Ron May.

EDITORIAL

Focus on the Future

The future works best for those who anticipate it. This idea was central to EPRI's founding, and the development of new technical concepts has remained an important Institute objective ever since. A still-sharper focus on the future through more-systematic exploitation of scientific advances was adopted several years ago with a decision to increase the Institute's commitment to exploratory research.

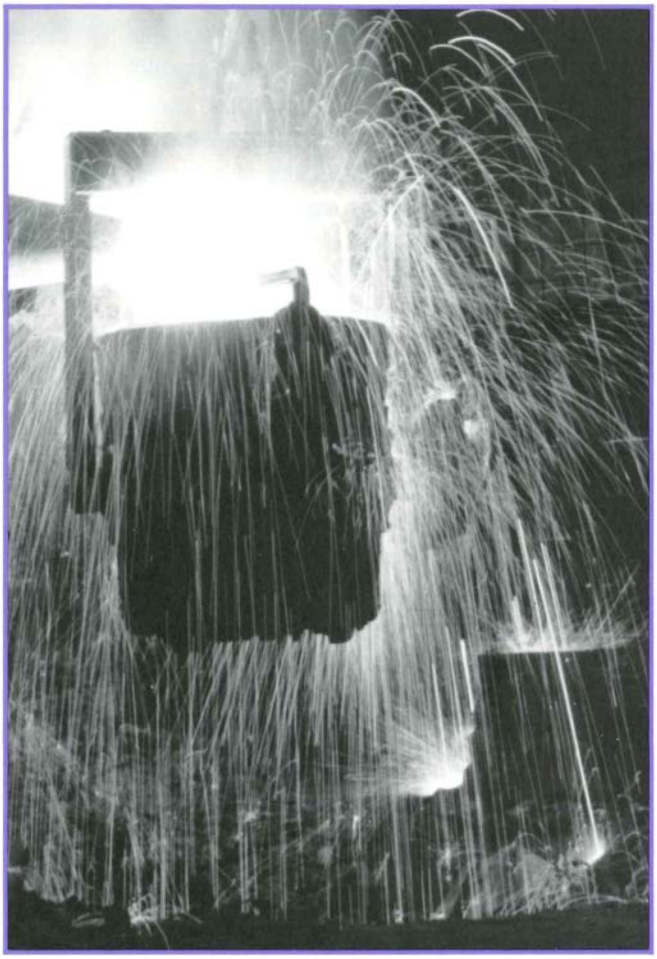
One key to the success of a technically broad-based but relatively modest exploratory program like EPRI's is to work with the best minds in the scientific and technological communities. This keeps us at the cutting edge in areas that we can expect to impact the future of electricity: low- and high-temperature superconductivity; chemical and biochemical processing of coal; new sensors and intelligent control systems; advanced algorithms and neural networks to handle large data sets and control complex systems; entirely new ways of using electricity to produce chemicals and clean up the environment; and many more.

The other key is to keep our eyes wide open: to see the connection between a scientific advance and its potential for a breakthrough in an apparently unrelated field; to pay attention to unconventional ideas even if they are being discounted by some experts; to spot the unexpected that may make a difference.

Conductive polymers, the subject of this month's cover story, are emblematic of the excitement exploratory research can engender. The very concept—plastics that behave as electrical conductors rather than insulators—seems counterintuitive. Yet basic science has postulated this possibility for some time, and laboratory exploration realized it almost 15 years ago. Today we can talk seriously about the idea of future polymer conductors that will combine the conductivity of copper with the strength of steel—without metals. Whether conductive polymers really will lead to big changes in the production, delivery, and/or use of electricity is still open. But we are now working with some of the leaders in this exciting field toward these long-term goals.

Not all of EPRI's exploratory work is at the beginning of the research and development cycle. A number of projects have already produced results that have clear value to the utility industry: development of very high performance, "clean" steels; enhanced understanding of coal structure and combustion chemistry; key insights into the growth and fabrication of crystalline silicon; and development of advanced power semiconductor devices for more efficient delivery and utilization of electricity. These results are now helping address utility needs we anticipated in the past. If we continue to commit to the future and keep the exploratory pipeline full, we can expect a steady stream of the innovation and advanced technology the industry and its customers will need to be successful in the decades to come.

Fritz R. Kalhammer, Vice President
Exploratory and Applied Research



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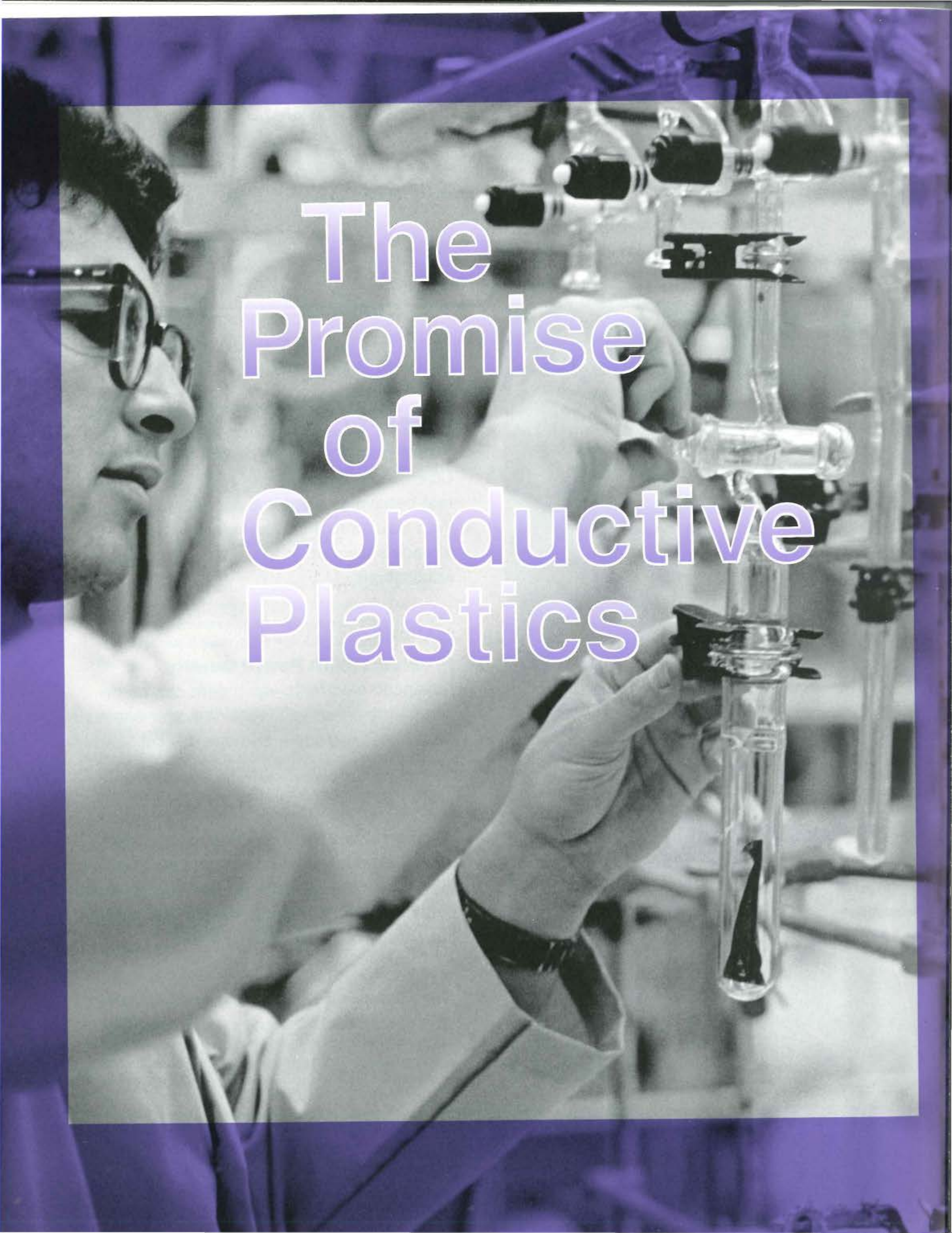
The Promise of Conductive Plastics



THE STORY IN BRIEF

Plastics that can conduct electricity would seem to have potential applications as broad as the spectrum of modern electricity use. Discovered nearly 15 years ago, these unusual polymer materials have only recently begun to appear in a handful of consumer and industrial products, including small, rechargeable batteries and high-tech sensors. But some chemical producers are sufficiently impressed with the possibilities to begin manufacturing conductive polymers in bulk. As a replacement for conventional conducting or semiconducting materials, the polymers could offer advantages in weight, strength, and durability; however, significant utility applications may be several years away.

A key feature that has always set polymers apart from metals or semiconductors has been their inability to conduct electricity. For this reason, many polymers have found wide use as excellent insulators. The insulation coating on electric wire and cable is typically made from polymers, and utilities are in the process of converting from ceramic-based insulated parts for many types of transmission and distribution equipment to parts made from polymers.

Yet in the past decade and a half, breakthroughs on a number of fronts have turned many notions about material properties upside down. For example, plastics need not always be insulators—some can be made to conduct electricity almost as well as metals. Science has discovered a new class of organic (carbon-containing) polymers that combine the electronic and optical properties of semiconductors and metals with the mechanical characteristics and processing advantages of plastics.

A group of scientists announced in 1977 that they had made certain polymers conduct electricity by chemically doping them in a way similar to that used to make silicon semiconductors. They also reported that the process by which the materials became conductive was reversible, meaning such polymers could be used to store an electric charge. At the time, there were predictions that paint-on plastic wires, plastic computer chips, lightweight batteries for electric vehicles and all sorts of portable gear, and even lightning-safe, plastic airplane parts would not be long in coming.

Many conductive polymers display one or more electro-optic properties, changing color or opacity in response to an electric field or a laser beam or increasing in conductivity with exposure to light. These properties make conductive polymers of interest for use in, among other things, so-called smart windows, which provide automatic shading or variable tinting.

Since 1977, researchers (mostly working at university and a few industrial laboratories) have focused on solving some of the real problems associated with processing and stability and with making practical use of the new materials in bulk form or as fibers, thin films, or electrically conducting blends with conventional polymers. Meanwhile, several chemical and material suppliers have begun producing conductive polymers and polymer blends in significant quantities.

A few conductive polymers have begun to show up in commercial products—for example, in specialized sensors and in small, high-energy battery cells. Several types of microelectronic devices using thin films of conductive polymer have been demonstrated. The combination of novel electrical and optical characteristics with the mechanical properties of plastic could lead to materials with many new applications as sensors, signal processors and switches, and display devices, as well as in high-speed computers. The materials are also being considered for use in a variety of forms as shields against electromagnetic interference and static discharge. Some researchers are pursuing biological applications of conductive polymers, including use in controlled-release systems for medicines.

"A large number of possible application areas are emerging as a result of recent progress, and I foresee established commercial uses in just the next few years—initially with materials in the intermediate range of conductivity," says physics professor Alan Heeger, one of the field's pioneers and the director of the Institute for Polymers and Organic Solids at the University of California at Santa Barbara. "Someday, one hopes to actually have polymers with conductivity greater than copper's and strength greater than steel's. Right now the work is at the level of basic science and is focused on understanding the intrinsic properties and the mechanisms of conductive polymers. But it doesn't look impossible. Even superconductivity may be possible, and we are making a serious attempt to look for it." (Superconductors are compounds that conduct electricity with little or no resistance losses when cooled to very low temperatures.)

Heeger and UCSB colleague Paul Smith have formed a company, UNIAX Corporation, in partnership with the Finnish state-owned oil and chemical company Neste Oy, for research and commercial development and application of conductive polymer technology. Meanwhile, Heeger and his group at UCSB are studying the fundamental limits of key conductive polymers with potential electric power applications under contract with EPRI's Office of Exploratory and Applied Research. More than two dozen promising applications of conductive polymers in the electric power field—ranging from bushings, cables, and capacitors to transformers, rotating machines, surge suppressors, sensors, and gas-insulated equipment—were identified in a recently released study for Oak Ridge National Laboratory and the U.S. Department of Energy.

"This is a very exciting area in which EPRI has begun some basic, long-range research that complements related work on polymer batteries already under way as part of a broader battery R&D program," says Fritz Kalhammer, vice president for exploratory and applied research. "The scientists who are making conductive polymers today tell us they are by no means at the end of what can be achieved in terms of conductivity, so much research is still focused on understanding the instrinsic properties of these materials. But the field is widely seen as one that could have a significant future impact in terms of how and where electricity is used." Conductive polymers will be one of the featured subjects at the EPRI-sponsored Electricity 2000 international forum, coming up in October.

An unexpected discovery

According to published accounts, the discovery of conductive polymers came, as important revelations often do, by accident. "It sprang from basic research, driven by simple curiosity, in which many scientists were looking into the electrical properties of a wide range of organic and inorganic materials," recalls Alan MacDiarmid, a professor of chemistry at the University of Pennsylvania and one of the codiscoverers of conductive polymers.

At one point the search led to the discovery, announced in 1975, of polysulfurnitride, an esoteric inorganic polymer that was inherently conductive and became superconductive when cooled to near absolute zero. Chemical researchers refocused their search on organic polymers, believing that those materials—if any were found to be conductive—would have the best hope of processibility using conventional plastics technology.

Around that time, Professor Hideki Shirakawa at the Tokyo Institute of Technology tried to synthesize the polymer polyacetylene from acetylene welding gas. Ordinarily a dark powder, the polymer had first been synthesized a quarter century earlier by a different method, but little was known of the material. This time, a student's error—overadding a catalyst to the reaction—yielded a new form of polyacetylene: a shiny, silvery, stretchable film.

MacDiarmid was shown the unusual metallic-looking film on a lecture visit to Japan in 1975. It became apparent that Shirakawa's group had created a polymer with an atomic bond structure that was very different from that of most polymers.

Polymers simply are repeating, chainlike molecules made by the union of smaller molecules called monomers. Polyacetylene is such a chainlike molecule, formed by the weak linkage of simple acetylene monomers, each consisting of a carbon atom with a hydrogen atom attached. In Shirakawa's new form of the polymer, the all-single bonds between the carbon atoms in the chain were replaced by alternating single and double bonds, providing a path on the atomic level for free electron carriers—that is, for the flow of current. But the polyacetylene film was not conductive, because there were no free electrons.

Intrigued with the film, MacDiarmid invited fellow chemist Shirakawa to join him and his physicist colleague Heeger (then at the University of Pennsylvania) for a year to study the material. When the three tried adding or removing electrons by chemically doping the polyacetylene, that is, adding oxidizing or reducing compounds—in this case, bromine, iodine, or arsenic pentafluoride in vapor form—the silver film turned a golden hue and became conductive.

With iodine doping, the researchers measured initial conductivity of approximately 60 siemens per centimeter. Before long, according to MacDiarmid, they had managed to push conductivity as high as 1000 S/cm by doping with arsenic pentafluoride. Doping gave the polyacetylene a conductivity comparable to that of doped silicon, although this level was far lower than the million S/cm characteristic of good conductors such as copper and silver. "A new era in polymer science was under way," says MacDiarmid.

Since then, researchers have discovered more than a dozen polymers and polymer derivatives that make the transition to a semiconductive or conductive state when doped. There are, in fact, families of conductive polymers, all consisting of repeating monomer units linked in chains. Most have varying numbers of carbon and hydrogen atoms in different arrangements; some, such as polyaniline and polypyrrole, have nitrogen in the backbone chain; others, such as polythiophene, instead include sulfur atoms.

Doping polymers to make them conductive is similar to the treatment of such semiconductors as silicon to make either p-type or n-type material. Because doping involves changing a polymer's electronic structure, scientists have used semiconductor band theory from solid-state physics to discuss the mechanisms of polymer conductivity (see sidebar).

Bridging the Electronic Energy Band Gap

Bands within a material's electronic structure reflect the different energy levels of overlapping electron orbitals of closely spaced atoms. A conventional material's electrical properties depend on the gap between the highest occupied (valence) energy band and the lowest unoccupied (conduction) energy band and on the extent to which the bands are filled with electrons. Completely filled or completely empty bands do not permit the flow of electron carriers, so no conduction occurs. If the bands are partially filled and the gap between them is narrow, thermal excitation of electrons from the valence band to the conduction band gives rise to conductivity, as in semiconductors. But if the band gap is too wide for electrons to jump, the material is an insulator. Metals are good conductors because their electronic structure has partially occupied bands or no band gap.

With conductive polymers, p-type doping (using iodine, bromine, or arsenic pentafluoride) removes electrons from the valence band, resulting in a partially filled band and giving rise to conductivity. N-type doping (such as with sodium metal) adds electrons to the conduction band, again making a partially filled band that gives rise to conductivity. "But [the polymers'] electrical conductivity cannot be fully explained by simple band theory," says Mercouri Kanatzidis, an associate professor of chemistry at Michigan State University and a researcher in conductive polymers, in a recent article. "To explain some of the electronic phenomena in these organic polymers, concepts from physics that are new for chemists, including solitons, polarons, and bipolarons, have been applied to conductive polymers since the early 1980s."

Kanatzidis says conduction by polarons and bipolarons, which are types of cations, is thought to be the dominant mechanism of charge transport in conductive polymers. The better scientists understand the mechanism of conductivity at the atomic level, the closer they can come to designing high-conductivity polymers.

Research leads to improved properties

When conductive polymers were first announced, recalls MacDiarmid, "there was a lot of research activity by a great many scientists, but it tended to die down after about five years because all the polymers at that point were insoluble, nonfusible, nonprocessible materials." Some of the doped polymers, such as polyacetylene, were also unstable environmentally, he adds, meaning that they degraded physically and electronically on exposure to air and sunlight.

Explains Sy Alpert, an EPRI executive scientist with a background in chemical engineering who manages Institute-sponsored work in conductive polymers, "The alternate single and double bonds between the carbon atoms in polyacetylene provide a path for electron carriers that makes the polymer conductive, but they are also the cause of the material's instability. Since the double bonds are open and able to conduct, they are also open to attack by oxygen. So the material tends to oxidize, pulling in oxygen atoms that break the polymer chain and make it chemically unstable."

Polyacetylene remains the polymer with the highest demonstrated, reproducible conductivity, 80,000 S/cm—less than that of copper on a volume basis but close to that of copper on a weight basis. But because it reacts with air and is neither soluble nor fusible, polyacetylene is considered to be among the least suitable polymers for near-term application. Polymers with better stability and processibility tend to have conductivities that are lower by one to three orders of magnitude (10–10^3 S/cm).

The pace of inquiry picked up again, says MacDiarmid, as a result of research breakthroughs by researchers that solved basic problems first of solubility for processing and blending and later of controlled orientation of polymer molecules for improved conductivity and mechanical properties. Working with polyacetylene, Heeger and MacDiarmid had shown in the late 1970s the key role that alignment of a polymer's chain molecules plays in its conductivity. Ronald Elsenbaumer of Allied-Signal is credited with forming the first soluble, solution-processible polymer, poly(3-alkylthiophene), in 1985. Heeger and Smith discovered, also in 1985, that orienting polymers such as poly(3-alkylthiophene) by means of various processing methods also increases their mechanical strength.

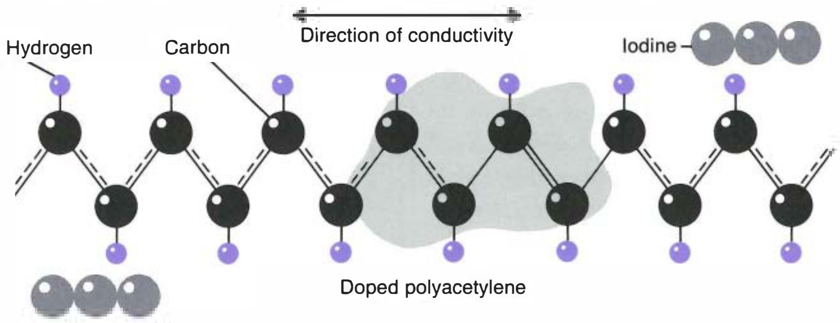
"With the understanding we have today, it's clear that we might have expected that the electrical and mechanical properties improve together as you orient and order the polymer chains, but the consensus in the field, even three years ago, was that you would never see that combination of properties. People just didn't believe it was possible," recalls Heeger.

DuPont researchers had first learned of the importance of alignment to a polymer's strength and stiffness some years earlier, but it was not until methods were perfected for achieving a sufficiently high degree of alignment that commercial applications of such polymers emerged. DuPont's oriented-polymer product Kevlar, with five times the strength of steel in one direction, is used today as a fiber in bullet-proof vests.

Researchers are pursuing several techniques for both blending conductive polymers with conventional polymers and orienting the conductive polymer so as to increase its current-carrying ability. These include conventional polymerization techniques of melt processing and solution processing, more recent methods such as spinning or casting from liquid crystal formations, and a new method—in situ, intercalative polymerization. In this technique, an oriented structure is first derived for the building-block monomers, which are then made to link together in an oriented, conductive polymer. "Order is the name of the game," says Mercouri Kanatzidis, an associate professor of chemistry at Michigan State University who is pursuing basic studies of conductive polymers, including in-situ polymerization techniques, with funding from the National Science Foundation.

Doping: The Key to Polymer Conductivity

Polymers are molecules of synthetic compounds formed by simpler monomers arranged into repeating, chainlike structural units. One of the most simple polymers, polyacetylene, is made by linking monomers of acetylene, each containing a carbon and a hydrogen atom, with alternating single and double atomic bonds. With p-type doping with an oxidant such as iodine, polyacetylene acquires a delocalized positive charge as the electron density (shaded area) smears along the backbone chain, enabling the material to conduct electricity. Near the negative dopant ions, the electron cloud diminishes and the distinction between double and single bonds blurs, as indicated by the broken lines. (Adapted from *Scientific American*, February 1988)



Conductivity and Resistivity: Flip Sides of the Same Coin

Materials are classified as insulators, semiconductors, or conductors according to their conductivity and resistivity—intrinsically related properties that vary inversely with each other along a logarithmic scale. Some well-known polymers, such as polystyrene, polyvinyl chloride, and polyethylene, are almost perfect insulators, while undoped polyacetylene and other conjugated polymers fall near the boundary between insulators and semiconductors. Many other doped polymers exhibit conductivities well within the semiconducting range, and doped polyacetylene can have intrinsic conductivity approaching that of some conductors.

Conductivity (siemens/cm)	Material	Class	Resistivity (ohm-cm)
10^6	Silver, copper, graphite	Conductors	10^{-6}
10^3	Tin, doped silicon, doped polyacetylene		10^{-3}
10^0	Doped polypyrrole and other conductive polymers		10^0
10^{-3}	Germanium, silicon	Semiconductors	10^3
10^{-6}	Silver bromide, iodine complexes		10^6
10^{-9}	Undoped polyacetylene, quartz, conjugated polymers		10^9
10^{-12}		Insulators	10^{12}
10^{-15}	Nylon		10^{15}
10^{-18}	Polystyrene, polyvinyl chloride, polyethylene		10^{18}

Moving from science to engineering

While much of the action in conductive polymers is still basic, laboratory-level science, the unique appeal of conductive polymers is rapidly propelling them into engineering development for commercial application. Chemical firms both in this country and abroad have recently announced that they have begun producing significant quantities of conductive polymers and polymer blends, signaling the start of commercial availability of bulk material for product development.

A worldwide renewal of interest in polyaniline, probably the oldest synthetic polymer, was initiated in 1984 by MacDiarmid at Pennsylvania in collaboration with Arthur Epstein of Ohio State University. They found that the polymer could be controllably and reversibly doped by simple aqueous acids, with a resulting increase in conductivity of 9–10 orders of magnitude. "We learned to process the material into freestanding films and fibers that could be mechanically oriented, for an increase in conductivity in the direction of stretching of almost two orders of magnitude," recalls MacDiarmid. "Even at today's early stage of development, the tensile strength of the fibers rivals that of commercial fibers such as the nylons, from which fishing line, among other things, is made," says MacDiarmid. The doped polymer is also stable in air at high temperature, he adds.

Heeger and Smith at UCSB, as well as other researchers, showed how to synthesize a conductive polyaniline derivative from sulfuric acid solution. Over the past decade, its chemical and molecular structure has been intensively studied at a number of laboratories. Several groups are working to synthesize new derivatives of polyaniline that have increased molecular weight for improved processibility, stability, and mechanical strength.

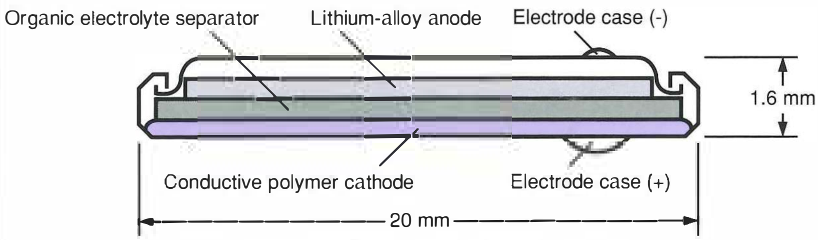
Polyaniline is one of the conductive polymers used in the small, rechargeable lithium-polymer batteries that recently became commercially available. According to MacDiarmid, who first demonstrated the polymer battery at laboratory scale, "polyaniline seems to be the best bet at the moment" for wider commercial application, although he notes that, despite its environmental stability, the material's conductivity—up to 200 S/cm in the oriented polymer—is not very high. Still, researchers note a wealth of potential applications, particularly as part of a blend of polymers, including use in electromagnetic shielding.

Rechargeable lithium-polymer batteries, the first commercial products based on conductive polymers, also use polyacetylene, polyparaphenylene, and polypyrrole in addition to polyaniline (or their derivatives) as the cathode material. A lithium alloy, such as lithium-aluminum, serves as the anode. Bridgestone Corporation and Seiko Electronic Parts in Japan and Seiko Instruments USA in this country are commercially producing a 3-volt, button-type battery using conductive polymer electrodes. In Europe, a joint venture between the German chemical firms BASF and Varta has commercialized a similar cell with a different polymer. Because of their long life and light weight (thanks to an energy density as much as twice that of nickel-cadmium batteries), lithium-polymer batteries are ideal for low-power applications, such as backup power for computer memory, and as a power source for small hand-held electronic devices and wristwatches.

In addition to the Bridgestone-Seiko and BASF-Varta ventures, other firms around the world, including Hitachi, Allied-Signal, and a joint venture between

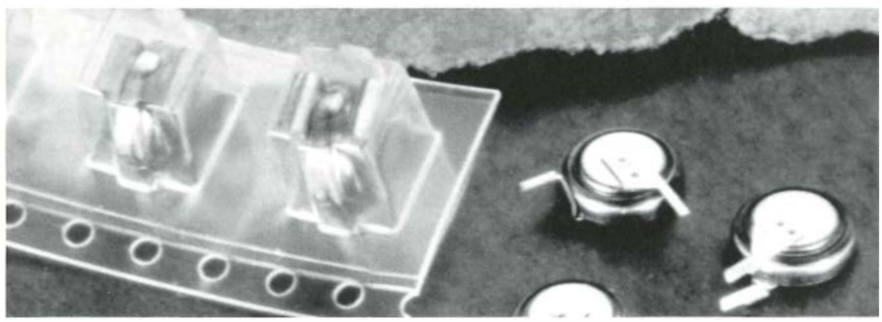
Polymer Batteries: Lightweight Upstarts

Small, low-power rechargeable batteries are among the first commercial products based on conducting polymers. Available from at least two producers, these batteries feature higher power and energy densities than most other battery materials. Lithium-polymer batteries are produced by Seiko Instruments USA in the form of 3-volt coin-type units that are used primarily for computer memory backup. Several companies reportedly are developing all-polymer, all-solid-state batteries that could be made in many shapes and sizes.



Lithium-polymer cell, Bridgestone-Seiko design

Seiko Instruments USA's lithium-polymer coin cells (Model AL Series)



Yuasa of Japan and Canada's Hydro-Québec, are reportedly pursuing all-polymer batteries. A solid, ionically conductive polymer electrolyte is combined with an electrically conductive polymer electrode to form an all-solid-state, flexible, laminate battery suitable for use in many shapes and sizes. If successfully developed, lightweight sheets of high-energy polymer batteries, stacked and connected in series to form high-current, high-capacity modules, could someday power electric vehicles or utility energy storage systems for meeting demand at peak periods.

Advanced batteries are only the first of what is expected to be a constellation of commercial applications of conductive polymers. Experts say the recent start of production of bulk material by some chemical companies reflects confidence that a wave of new product development may be gathering momentum. Neste has begun pilot-scale production of solution- and melt-processible polythiophene derivatives and polyanilines in Finland. Last May, Allied-Signal announced that it had developed, together with Zipperling Kesler and Americhem, an intrinsically conductive polymer with a wide range of technical applications, particularly in electromagnetic shielding and electrostatic dissipation. Allied-Signal said the polymer, reportedly a derivative of polyaniline, is environmentally stable and will not lose conductivity under typical use conditions. Zipperling Kesler, a German firm, and Americhem, based in Ohio, are producing blends of the conductive polymer with polyvinyl chloride for commercial application.

Power applications assessed

Many potential electric-power-related applications of conductive polymers were identified and evaluated a couple of years ago in complementary studies for EPRI and DOE. In a 1989 study for EPRI, as yet unpublished, Battelle, Columbus Laboratories, surveyed the chemistry, theory, and current limitations of the materials. The study also highlighted a framework for research to develop applications of interest to utilities, including use in batteries, transmission and distribution equipment, and photovoltaic and other electronic devices.

A Spectrum of Present and Potential Commercial Applications

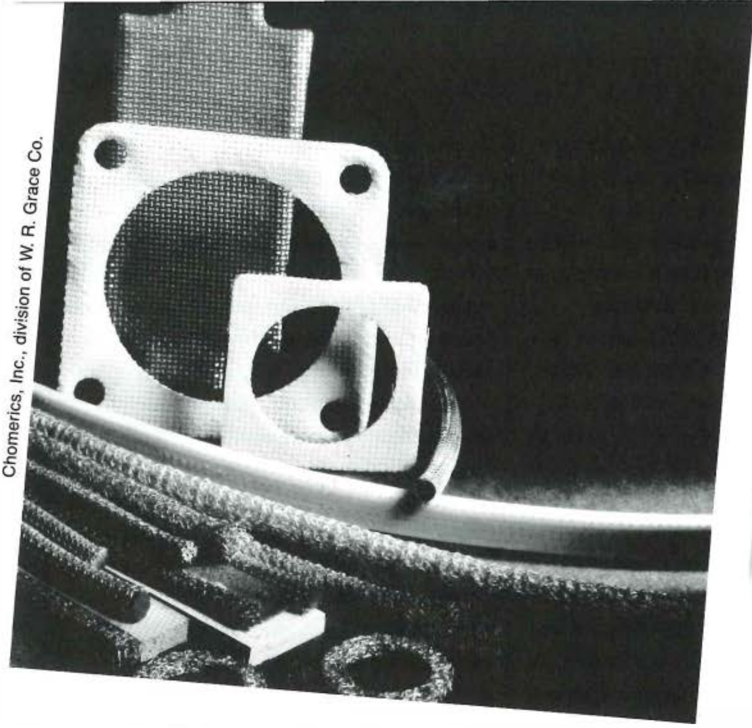
Conductive polymers are already used in several commercial products and potentially could play a role in a broad range of consumer and industrial technologies. In addition to being used in computers, lithium-polymer batteries power some credit card calculators. The electronics and materials technology firm Raychem Corporation uses conductive polymers in a variety of industrial products, including self-regulating heat-tracing systems, leak-sensing cables, and overcurrent protection devices. Some aircraft makers reportedly are experimenting with conductive polymers in advanced, lightweight composite aircraft parts that are resistant to electromagnetic interference and lightning.

Raychem Corp. heat-tracing and leak-sensing systems

Aircraft parts for lightning-strike and EMI protection

Bettman Archive

Credit card calculator powered by lithium-polymer laminate battery



Commercial EMI-shielding products and antistatic devices

Allied-Signal scientist demonstrates the electrostatic dissipation properties of a new conductive polymer blend.

Applications in EMI Shielding and in Antistatic Devices

Materials that absorb or cancel electromagnetic interference are incorporated into products ranging from computer equipment to automotive electronics to various components of weapons systems. Most applications of EMI shielding today involve the use of metal mesh or spray-on coatings, or metal-particle-filled composite material. Products in a related application area—those that dissipate electrostatic charge—typically employ carbon-black-filled materials or coatings. Intrinsically conductive polymers potentially could serve as lighter-weight, less expensive, and more effective EMI-shielding and antistatic materials.

The study for DOE assessed the opportunities for using polymers with conductivities as high as 2000 S/cm, such as are currently under development, in electric power equipment where electrical stress grading is an essential design feature. It also identified the R&D that would be necessary to develop the materials to the point where they could fully compete with currently used conventional materials.

Several potential electric-power-related applications involve the substitution of conductive polymer for carbon black that is blended with nonconductive polymers such as polyethylene. This semiconducting material is used where it is necessary to dissipate static electric charge that might otherwise accumulate and cause flashover, or electrical failure. Similarly, conductive polymers potentially could replace conductive fillers such as metal particles, flakes, or fibers dispersed in conventional matrixes to form electromagnetic-shielding material. For many such applications, conductive polymers promise reduced weight, improved strength and mechanical properties, and greater durability. Such advantages reportedly have been seen at the laboratory test scale.

But as the study for DOE and Oak Ridge National Laboratory noted, a wide range of properties and characteristics of conductive polymer materials must be thoroughly investigated before prototype development can begin in many of the promising applications that have been identified. These include compatibility with other materials, long-term stability at elevated temperature in various environments (including high electric fields), and stability under manufacturing conditions.

According to the DOE-ORNL study, conducted by Westinghouse Electric, conductive polymers such as polypyrrole, polythiophene, and polyaniline are unique in several ways: their conductivity can be tailored over a range of 10^{-8} to 10^{3} S/cm; they can be prepared as coatings or bulk material; and, compared with carbon black, they have improved compatibility with other polymers. Such properties give rise to hopes that power equipment applications of conductive polymers could offer improved reliability, simplified manufacturing, and reduced operating losses.

The most promising applications to emerge from the DOE-ORNL study's systematic ranking on the basis of technical and economic impact, chance of success, and required development time involve capacitors, rotating machines, bushings, and gas-insulated equipment. All the highly rated possibilities require material conductivities well within the range of the three most promising conductive polymers and their derivatives.

For example, conductive polymers could be used as a coating of dielectric film in capacitors that would short-circuit voids between films and inhibit partial discharges. A similar semiconducting coating extending from capacitor electrodes could reduce voltage stress at the electrode edge and extend a capacitor's operating life.

Likewise, a surface coating to dissipate charge over the insulator surface of high-voltage bushings would reduce the chance of flashover, a major cause of failure in such equipment. Or a conductive polymer could be blended with a bulk resin in the manufacture of such parts in order to control the internal electric field distribution and extend the life of the insulation.

Several applications of conductive polymers were highly rated for the potential to improve the high-voltage-withstand capability of support insulators for gas-insulated equipment. They include insulator coatings to control surface conductivity, insulator filler to control bulk conductivity, and the insulator-conductor interface. To the extent that such surfaces could be made semiconducting, they would inhibit charge buildup in metallic particles that then accumulate at the surface and eventually reduce the equipment's high-voltage reliability.

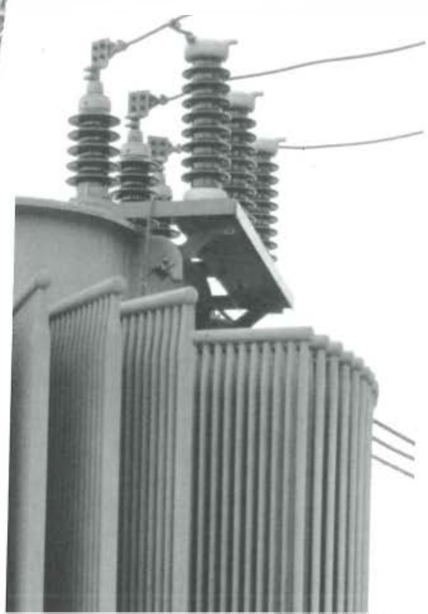
In rotating machines like generators, conductive polymers could replace the carbon-filled epoxy resins used by some manufacturers to reduce electromagnetic field stresses at conductor protrusions. Conductive polymers, the study found, should be more compatible with the resin polymer and offer greater control over conductivity than the currently used mixtures. Other highly rated uses in rotating machines are as a replace-

Utility Possibilities Span Generation, Transmission, Distribution

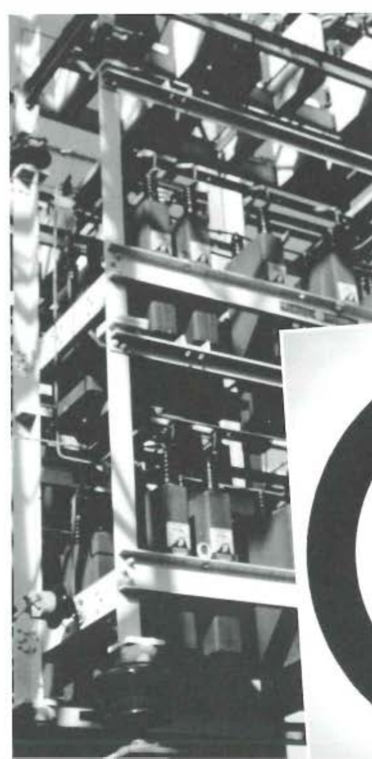
Utilities may someday be significant general users of conductive-polymer-based products such as batteries and sensors. Yet even at their present level of development, conductive polymers have also been considered for a wide range of possible future applications in utility equipment, from capacitors and cable components to generators, bushings, and conductor couplings. Most potential applications involve equipment parts that must be semiconducting for electrical stress grading or electrostatic charge dissipation. If they can be developed with acceptable performance and attractive economics, conductive polymers may someday replace carbon black and metallic conductive filler materials that are added to make some components semiconducting. Other possible uses not yet evaluated in detail include magnetic-shielding material.

Generators
(coatings, static brushes, tape)

Transformers
(conductive paste and putty)



Capacitors
(component coatings)



Solid dielectric cables
(conductor and insulator shield

ment for carbon in static-dissipating brushes for turbine generator shafts and as a coating or tape to short-circuit gas gaps in stator slots.

In power transformers, conductive paste or joint putty for use in cable connectors and wrapped insulations might be superior to currently used materials because of greater compatibility between conductive polymers and other organic resins. Use as a semiconducting coating in transformer components was also judged technically attractive. Likewise, conductive grease for use in cable connections is a promising application: because a conductive polymer can be more easily and thoroughly dispersed in an organic base material, improved control of material conductivity over a wider range is possible than with present graphite-loaded or silicon carbide–loaded conductive greases.

Both the DOE and EPRI studies noted that conductive polymers are of interest for replacing carbon black as the conductive filler in ethylene copolymers used to make conductor and insulator shields for solid dielectric cables. Although carbon black imparts the desired electrical properties, it is not transparent to the far-infrared (FIR) light employed by a new laser scanning technique for void detection. Any new conductive polymer used in a blend in an extruded insulation shield material would have to be compatible with the copolymer-curing process and remain stable with aging.

In a project for EPRI a couple of years ago that was related to work on FIR inspection methods, Westinghouse tried blending ethylene copolymers with various conductive polymers in hopes of producing a material that could be used as a carbon-free, FIR-transparent system. Initial results fell short of the required combination of semiconducting and FIR-transparent properties, and the project has not been pursued further.

Independent of their FIR transparency, conductive polymers are also of interest as a replacement for carbon black in conductor shields. "We think this is a technically solvable problem," says Bruce Bernstein, a project manager in EPRI's Electrical Systems Division. "It really is a question of whether this would lead to cable materials that perform as well as or better than present, proven materials but don't cost significantly more. This would require some additional development to determine."

High-power applications a decade away?

Indeed, most of the electric power applications of conductive polymers with the greatest value to utilities are likely to require many years of further material and prototype development, followed by the gathering of a substantial body of operating test data. Only then can conductive polymers be expected to show up significantly in power system components and materials. Such applications represent the ultimate challenge for conductive polymers in terms of reliability and performance. "Utility applications will probably be one of the last application fields for conductive polymers to penetrate," says EPRI's Sy Alpert. "Even if developers solve all the problems of fabrication and conductive polymers turn out to be compatible with what our industry's equipment suppliers are using now, it will take some time for such new materials to be accepted by the industry.

"That's why it's fortunate there are some very promising early applications in the industrial and consumer products sectors, including batteries and antistatic devices, that don't have to meet the rigorous standards of reliability that apply to utility equipment. They provide early markets that help drive down the cost of the new materials.

"Conductive polymers are easily 10 years away from having an impact on the way utility engineers do their jobs, but that's part of what EPRI is for," adds Alpert. "At the moment, we just have a toehold in this field. We're trying to build on the science and get a good understanding of the potential. Right now, it's a research idea, because we keep defining issues. But at some point, you can't establish the value of something any further unless you do some engineering analysis. That hasn't started yet, but it will soon. My own hope is that with continued progress, the next generation at EPRI will be considering conductive polymers as a potential program area."

But perhaps soon, long before they make their way into high-power equipment, conductive polymers may begin appearing in a number of niche applications. Observes Alan Heeger: "Over the last 10 to 15 years, we have built a scientific base of understanding in conductive polymers and solved enormous problems of processing. Science is in a position to begin to take advantage of the dream of uniting in truly unique materials the properties of electrical conductivity and the mechanical and processing advantages of polymers. We are doing that today." ■

Further reading

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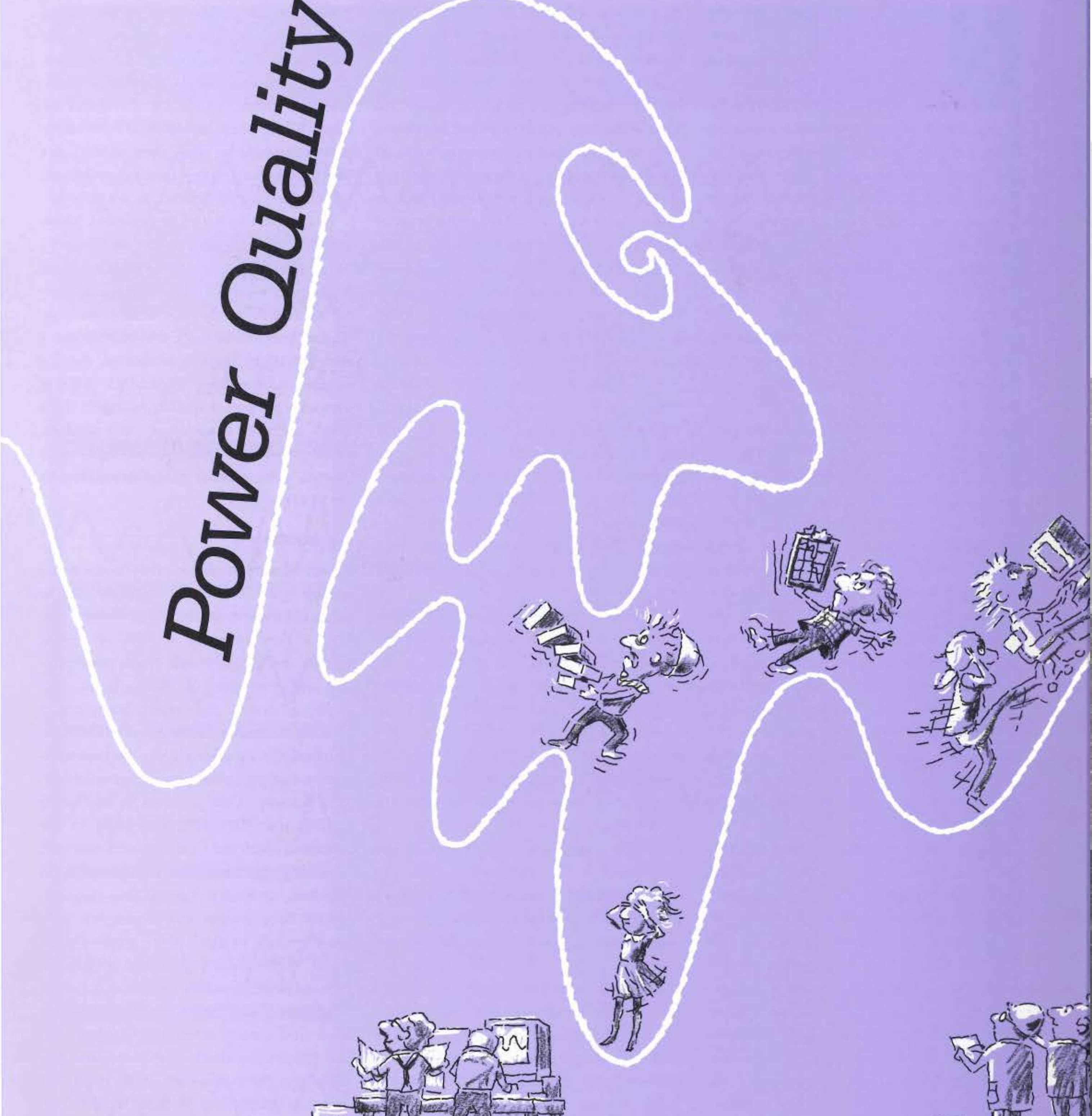
This article was written by Taylor Moore. Background information was provided by Seymour Alpert, Office of Exploratory and Applied Research.

THE STORY IN BRIEF

The advanced electronic equipment that has brought efficiencies to our homes, offices, and factories has introduced some problems as well. Much of this equipment is uncommonly sensitive to routine power line disturbances, and some devices even create their own disturbances that feed back onto the utility line. Industries have been hit particularly hard, with momentary outages at some plants costing $300,000 per incident. EPRI is working with utilities, their customers, and manufacturers to develop and implement cost-effective remedies.

Problems With

Power Quality



Nabisco figured it was making a great investment in the future of its 77-year-old Shredded Wheat plant in Oakland, California, when it bought six adjustable-speed drives a year ago. Plant managers were looking forward to better control of the production line and lower maintenance costs. Instead, the drives began tripping off at 9:25 every morning. "You could set your watch by it," recalls plant maintenance manager and engineer Richard Parks.

The conveyor loaded with layered dough would grind to a halt while the shredder, controlled by a separate drive, continued. The result was a sizable, sticky mess. Typically it took about 20 minutes to clean up equipment and set the production line back in motion. With the cost of downtime running at $1680 an hour, the losses began adding up.

Nabisco's problem was related not to improper installation of the new drives but to power quality. Unlike the former electromechanical equipment on the line (gearboxes with chains and pulleys), the electronic adjustable-speed drives were sensitive to transient overvoltage. This condition was created when the local utility switched its capacitors, as it had done routinely for a number of years, to keep the voltage level up on the power line. Nabisco's case is just one example of the kinds of power quality problems that can arise in industrial plants today.

In addition to traditional power quality problems caused by improper grounding and wiring and by natural disruptions like lightning, a wide variety of industries across the country are finding that their automated electronic equipment—including adjustable-speed drives, programmable logic controllers, and power supplies in computers—is vulnerable to overvoltage, undervoltage, momentary interruptions, and other disturbances that have always existed on the utility power line. Much of this advanced equipment also generates disturbances back onto the utility line.

One result of all of this has been a series of mysterious mishaps on America's factory floors. Automobiles have been pushed through production lines too swiftly, resulting in a paint coat that is too thin. Automatic embroidering machines have sewn garbled names onto hats. At one food processing company, mounds of cheese clogged up a production line so badly that it took four days and a crew of eight to extract the gluey material from the machinery. There have even been cases in which equipment at one plant has disrupted the operations of a neighboring facility drawing power from the same utility line.

While this new generation of power quality problems has affected the residential and commercial sectors as well (blinking clocks and scrambled computer data are two manifestations), the most significant losses have resulted in the industrial sector. One U.S. automobile manufacturer reports that momentary outages at its plants cost as much as $300,000 per incident.

"Power quality goes down to the bottom line—that's why so many people are so interested in it," says William M. Smith, who has overseen much of the power quality work in EPRI's Customer Systems Division. "Sometimes it's only a nuisance. But other times it means big losses." Just how much these losses add up to nationwide is difficult to determine. A study conducted by a manufacturer of power-quality-monitoring equipment cites a figure of $1 billion. But according to an estimate published in *Business Week* (April 8, 1991), power quality problems are costing U.S. manufacturers $26 billion a year to accommodate and correct.

"The numbers are all over the place," says Marek Samotyj, senior project manager for power quality at EPRI. Samotyj, who is helping organize an international conference on power quality, says experts from around the world have also been unable to turn up a single, reliable figure for their countries. The problem, he says, is that more work has to be done to define power quality problems. "People are not making a distinction between the reliability issue and power quality," he explains, noting that natural disasters like tornadoes can knock out electrical systems for days. While such incidents are certainly power-related, he says, they should not be classified as power quality problems, which are strictly related to waveform.

In an effort to better understand, characterize, and resolve power quality problems, EPRI has been studying the issue from both sides of the meter—the customer side as well as the utility side. For related projects in the Customer Systems and Electrical Systems divisions, the Institute is spending about $3 million annually on power quality research. This work includes a series of case studies, from which the Nabisco example was drawn. (The sidebar offers more details on EPRI's work.)

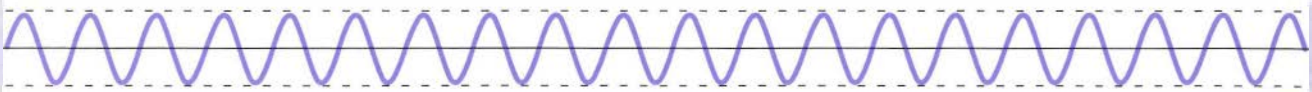
No mystery

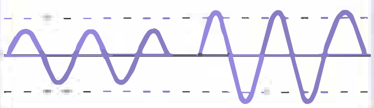
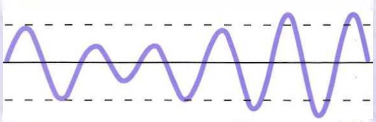
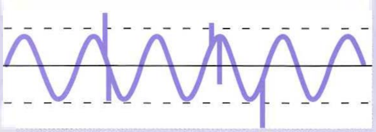
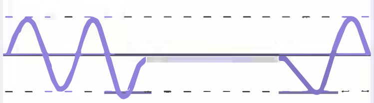
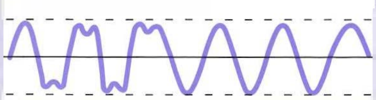
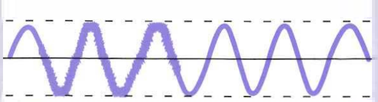
Power quality problems may seem enigmatic, but they are actually fairly straightforward. In fact, EPRI's work has shown that as many as 80% of power quality problems result from poor wiring and grounding (including loose connections) on the customer's premises or from interactions between on-site loads. "Sometimes we jokingly say the best mitigation equipment is a good screwdriver," says Samotyj. One problem is that while wiring and grounding according to the National Electrical Code ensures safety, it does not promise that equipment will function properly. Grounding requirements have grown more complex with the evolution of modern electronic equipment. While older equipment required a ground only for safety purposes, modern equipment also relies on a ground for logic and system reference. Guidance on the proper installation of computer systems and other sensitive loads is offered in publications like Federal Information Processing Standards Publication 94.

"There is nothing mysterious about power quality—nothing," says Samotyj.

In Search of the Perfect Wave

Normal power



Type of Disturbance	Description	Protective Equipment
Undervoltage, overvoltage 	Abnormally low, high voltage lasting more than a few seconds	Voltage regulator, line conditioner, or uninterruptible power supply (UPS)
Sag, swell 	Momentary decrease, increase in voltage lasting less than a few seconds	Voltage regulator, ferroresonant transformer, line conditioner, or UPS
Surges, spikes, impulses 	Voltage increases lasting from microseconds to milliseconds	Surge suppressor or line conditioner
Outage 	Complete loss of power lasting from several milliseconds to several hours	UPS, standby power supply, or motor-generator set
Harmonic distortion 	Continuous distortion of the normal sine wave, occurring at frequencies between 60 Hz and 3 kHz	Filter or isolation transformer
Electrical noise 	Continuous distortion of the normal sine wave, occurring at frequencies above 5 kHz	Grounded shielding for cables, equipment, or walls of a room

"Once you learn the basics, you see that everything can be predicted, modeled, and then solved. However, there is a need for a well-thought-through engineering and economic approach to power quality problems—an approach that could be provided by an expert system—matching causes to proper mitigation schemes." EPRI plans to initiate work on such a system next year.

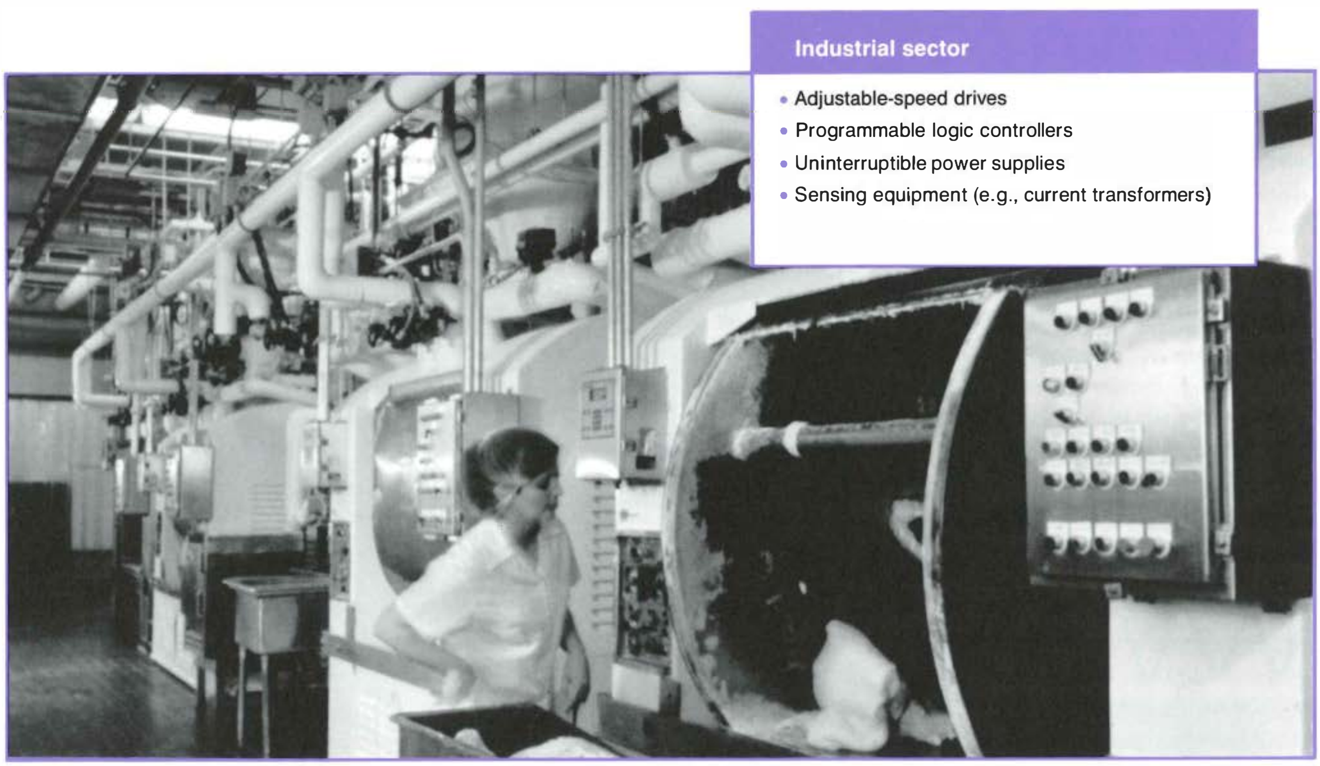
Often problems result when two pieces of equipment draw power from the same circuit. One example occurred at the Gaithersburg, Maryland, campus of the National Institute of Standards and Technology (NIST), formerly the National Bureau of Standards. A coffeepot plugged into the same receptacle as a personal computer scrambled data on the PC every time its heater cycled on or off. Obviously, no expensive power-conditioning equipment is necessary to correct such problems.

For power quality problems that are not related to wiring and grounding, there are all kinds of remedies available today. These range from a simple $10 surge suppressor that can be used for a PC in the home to an uninterruptible power supply (UPS) unit for a mainframe computer system. Large UPS units can cost more than $100,000. In fact, doctoring power quality problems is big business: the market for products and services in the United States alone is at least $1.2 billion annually, according to one power quality consultant.

Matching a solution to a given problem requires some expertise. But the real challenge is finding the most cost-effective way to solve the problem. In the Nabisco case study, for instance, the Oakland plant management considered purchasing a $2500 power-conditioning filter typically used to solve transient overvoltage problems. But careful diagnosis of the problem revealed that a much simpler, less expensive option, a $150 coil that functions like a choke, would work even better. The company installed four coils—one on each problem drive. This fix immediately resolved the problem. Now Nabisco's national management is recommending this solution to all of its other U.S. plants that have experienced similar problems.

A New Generation of Power Quality Problems

The past decade has brought a rapid increase in the use of advanced electronic equipment in our homes, offices, and industries. Much of this equipment is sensitive to disturbances that have always existed on the power line. Some of the devices even generate disturbances back onto the line. While these problems have affected all sectors, industry has suffered the biggest monetary losses.



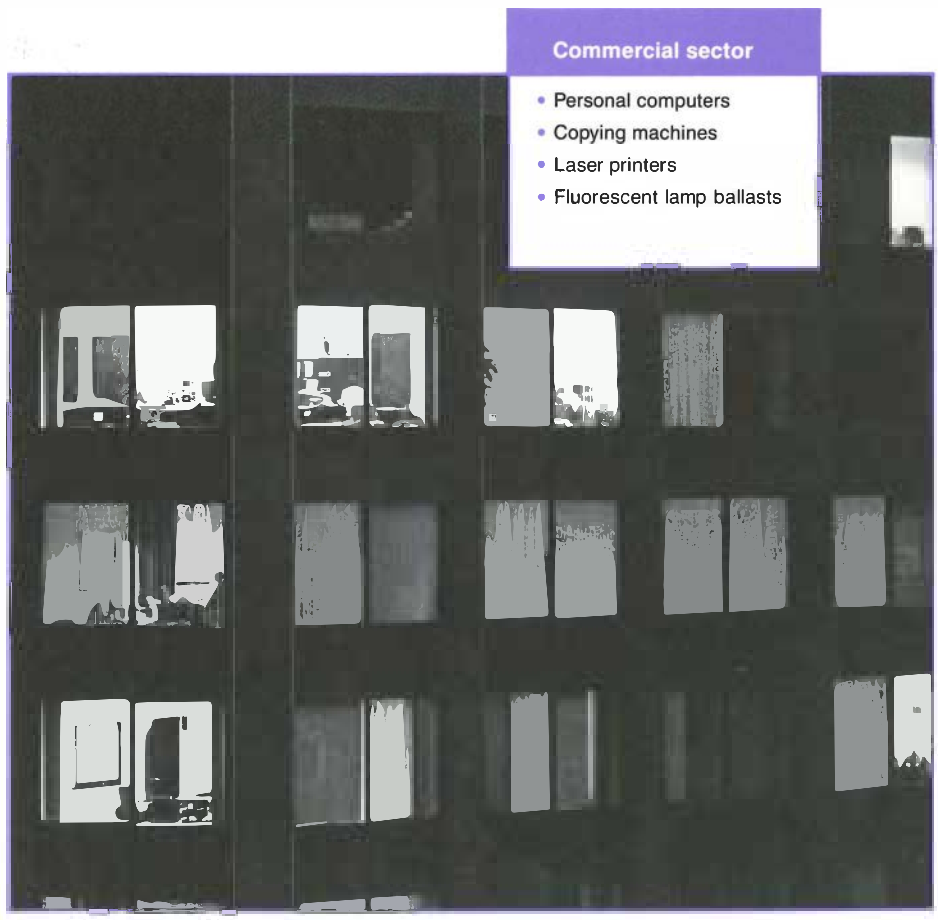
EPRI's case studies also have shown that mischaracterizing a power quality problem can sometimes lead to the employment of an improper or more expensive solution. For instance, researchers discovered that a number of industrial customers were diagnosing voltage sags as outages. As a result, they were considering purchasing expensive UPS units, a typical remedy for outage problems. Once EPRI's experts determined that the real problem was voltage sags, they were able to recommend the implementation of ferroresonant transformers, which cost $600 apiece, about 20% of the cost of the UPS units under consideration.

Reaching the customer

While there are solutions available for virtually every power quality problem that exists today, EPRI has found that utility customers typically do not have the expertise on staff to diagnose these problems and come up with the best solution. "Power quality issues are so new that there really aren't many experts out there," says Smith. "We have most of them under EPRI contract at this point." EPRI is helping bridge this knowledge gap through projects like the case studies. As Smith points out, one nice side benefit of the case studies is that they have provided a good catalyst for getting utilities and their customers to work together more closely.

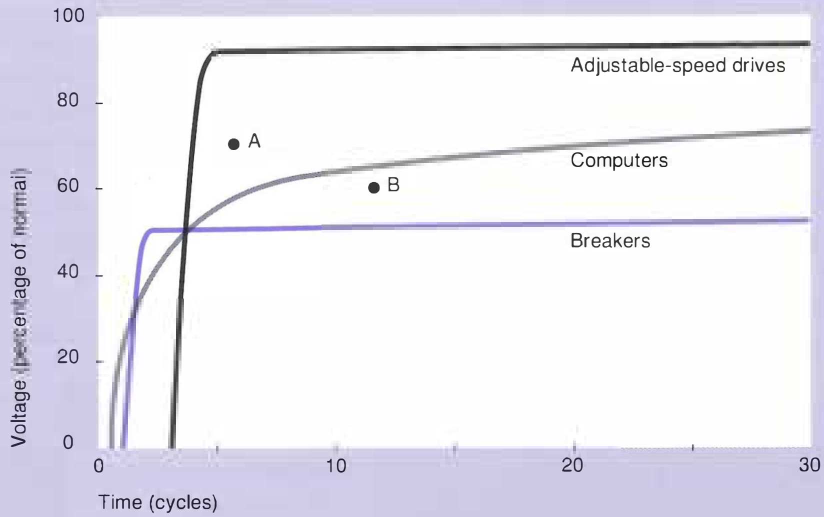
But EPRI isn't the only one providing assistance. A number of utilities that have their own experts on staff are working directly with their customers to resolve power quality problems. About 10% of EPRI members have even established power quality programs to respond to customers' concerns. The programs vary from utility to utility, offering services ranging from free analysis to power-conditioning equipment sales. Baltimore Gas & Electric is believed to be the first utility in the country to create such a program. Called Premium Electric, the program was established in 1984 in response to an increasing number of customer complaints about new equipment not operating properly.

"There was really no one else to turn to at the time, so we picked up on it ourselves," says Tom Hellman, senior engineer and one of four employees in the



Victims

Advanced electronic equipment is more sensitive to power disturbances than traditional machinery, as this graph of sensitivity thresholds illustrates. For instance, a voltage sag resulting in 70% of normal voltage for six cycles (point A) will trip an adjustable-speed drive (ASD), while neither computers nor breakers will be affected. A voltage sag to 60% at 12 cycles (point B) will affect computers as well as ASDs but still lies outside the sensitivity threshold for breakers.



program. Services include on-site diagnosis of customer problems, recommendations of solutions, and even the sale or lease of power-conditioning equipment. There is no charge for services unless an outside consultant is required. A small percentage—enough to cover the utility's administrative expenses—is added to the cost of equipment leased or sold.

Increasing customer complaints about power quality problems also led PSI Energy, formerly Public Service Indiana, to create a special program. Called Power Clinic™, the program was established in 1987 and is staffed today by two full-time people. More than 250 other utility employees have been trained to offer power quality troubleshooting on an occasional basis. One of the program's main thrusts has been education. PSI has hosted a dozen half-day seminars for customers and has also offered an introductory course on power quality to contractors and electricians through the Electric League of Indiana.

One of PSI's first cases involved a wire manufacturer that had installed some adjustable-speed drives along its production line. Voltage sags, which in the past had only caused lights to flicker, began tripping off the new drives. After each occurrence it took two days to extract the tangled web of wire from the machinery and set the line back in motion. Various suppliers recommended solutions to the manufacturer, including a $250,000 UPS. But the Power Clinic staff was able to work with the drive manufacturer, who agreed to add some additional ride-through capability to the drives. This resolved the problem for about $2500.

Like Baltimore Gas & Electric, PSI does not make a profit on such services. "We look at it this way," says Greg Porter, who formerly managed Power Clinic: "Helping customers out with these kinds of problems and making them happy is only good for our business." Such utility programs are a reflection of how the industry has grown more customer-focused, Smith says. "You can win two ways in the marketplace," he says. "You can be the low-cost provider and offer a quality product at a cheaper price than anyone else, or you can differentiate your service and offer features that your competitors, like independent power producers, can't—such as services to help customers with their power quality."

There are a few utilities in the country that have taken the notion of power quality programs beyond the customer service level and have established for-profit power quality subsidiaries. Portland General Electric is one of them. Its subsidiary, called Portland General Energy Systems, was established in November 1989 and is just starting to turn a profit, with gross annual sales now over $1 million. Staffed by 14 employees, the business has positioned itself as a specialist in power quality, selling training, monitoring, and diagnostic services, as well as equipment.

Often the firm is hired by developers, architects, and engineers. Gerry Kuhel, manager of business development, likens the subsidiary's role to that of a lighting designer's. "A number of years ago the lighting designer emerged as a new professional, and people discovered there was more to lighting than meets the eye," he says. "Our business is similar. We are power quality designers. We too are part of the design team." Kuhel says the subsidiary's goal is ultimately to expand into a regional power quality center that would serve the northwestern states.

Working with manufacturers

As the burgeoning market for power-conditioning equipment and services indicates, there is plenty of incentive to solve power quality problems by shielding the customer's premises. But another, often more cost-effective approach is to resolve the problems at the design level, making changes in the products that either are sensitive to power disturbances or create disturbances on the power line. This tack, which involves working closely with manufacturers, has been the main objective of EPRI's Power Quality Test Facility (PQTF) at the Institute's Power Electronics Applications Center (PEAC) in Knoxville, Tennessee.

The test facility, which opened about two years ago, is equipped with a 100-kW power station that can generate distorted waveforms to simulate the gamut of power quality problems. The facility's staff of six has been busily zapping an array of products—from deep fat fryers to programmable logic controllers—with a variety of "dirty" power. The intent is to determine how sensitive these loads are and how to make them resistant to power disturbances. Among the manufacturers whose equipment has been tested are ABB Asea Brown Boveri, Allen-Bradley Company, and General Electric.

"We see our role as trying to identify those obviously economic things you can do at the load end," says Tom Key, manager of PQTF. For instance, one PQTF study concluded that a $2 modification to a programmable logic controller's power supply would make it immune to the most common power disturbances. As Key points out, there are no massive profits luring entrepreneurs to approach the power quality issue from this angle. But there's great incentive for utility industry involvement. "Nobody can benefit more from improving load tolerance than the utility and its customers," he says.

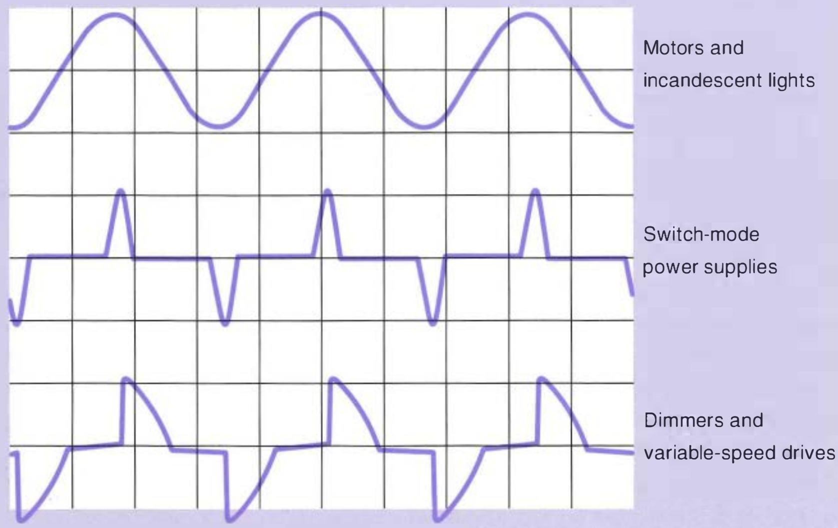
Since few manufacturers have power-testing facilities and none has anything as extensive as PQTF's, some have viewed the Knoxville laboratory as a useful resource and have brought their equipment in for testing directly. But so far, most tests have been conducted—with the consent of manufacturers—at the request of utilities whose customers rely on the products of concern. PQTF recommendations are published and issued to the parties involved. The findings are also made available to standard-setting organizations like the Institute of Electrical and Electronics Engineers (IEEE), with the names of the manufacturers withheld. According to Key, the aim is to provide objective information that manufacturers can use to make their equipment more compatible with the utility power system.

In an effort to reach more members of the manufacturing community, PEAC recently established a nonprofit power quality network. So far, four U.S. universities and two government agencies, NIST and the National Research Council of Canada, are network members. PQTF staff will serve as project coordinators of the network. NIST's role is strictly advisory: offering assistance with techniques and procedures used to gauge power quality. Laboratories and equipment of the other members will be used for testing and field work similar to that conducted at PQTF. The university laboratories—at California Polytechnic State University in San Luis Obispo, the University of Florida, Wichita State University, and Worcester Polytechnic Institute—are being cosponsored by their local utilities. The network's first project, testing high-frequency electronic ballasts, is expected to get under way in August.

PQTF staff members plan to use findings from the network's laboratory and field tests to help write criteria that will define a "utility compatibility" concept. The criteria will specify a certain level of immunity to power quality disturbances for each load. EPRI's ultimate vision, which would have to be implemented by standard-setting bodies, is a UC label on products that meet the utility compatibility criteria specified.

...and Villains Too

Traditional, electromechanical equipment will draw sinusoidal current from a sinusoidal voltage. But electronic equipment, which converts ac power to dc power, does not draw current for the entire voltage waveform interval. The resulting current irregularities can cause disturbances, such as impulses and voltage loss, on the power distribution system.



Load current waveforms

Tackling Power Quality Issues on Both Sides of the Meter

EPRI's Customer Systems and Electrical Systems divisions have initiated complementary projects to enhance the quality of power on both sides of the meter—the end-use side as well as the utility side.

On the end-use side of the meter, EPRI has completed about half of 21 designated case studies involving utilities' customers. Under way since the fall of 1989, the studies have included a variety of industries, from food processing to semiconductor manufacturing, as well as commercial buildings. Pacific Gas and Electric has cosponsored the bulk of these studies. Four other utility organizations—Commonwealth Edison, Central Hudson Gas & Electric, Delmarva Power & Light, and the Kansas Electric Utilities Research Program—are also participating. The studies are expected to be completed in 1992.

Other work on the end-use side of the meter is focused at the Power Quality Test Facility (PQTF) within EPRI's Power Electronics Applications Center in Knoxville, Tennessee. There manufacturers' products are tested in a state-of-the-art laboratory that can simulate power disturbances. To add a real-life dimension to lab findings, PQTF staff members periodically explore and solve specific problems in the field.

On the utility side of the meter, EPRI has initiated two major power quality projects. In a power quality assessment study, the Institute is installing 300 power nodes on utility lines across the country. Beginning this fall, the nodes will be placed at three locations—at substations, in the middle of lines, and at customers' service entrances—on the lines of each participating utility. The units will stay in place for two years. The data gathered will characterize the kinds of disturbances detected and the frequency of these disturbances. All results will be available by 1994.

A second major supply-side project, a 10-year initiative called Custom Power, has been under way since 1989. This effort involves the development of advanced technology that will allow utilities to offer very high quality power to customers with sensitive loads. Although a premium may be charged for custom power, the added service value would easily outweigh any increased costs.

While there are a number of power quality remedies on the market today, the bulk of these are so-called passive solutions, which typically cannot respond to a variety of conditions. EPRI has focused on developing active solutions for both sides of the meter. Active solutions use power electronics to sense an existing condition and respond appropriately, in real time. Four of these technologies—expected to be commercialized between 1992 and 1994—are described below.

Active power line conditioner Like the passive harmonic filters available today, this technology will correct harmonic distortion. But while one passive filter can typically reduce harmonics of only one frequency, a single active power line conditioner can correct harmonics at a variety of frequencies. This technology cleans up distorted voltage received by a piece of equipment, as well as disturbances generated by the equipment. Other benefits include correction of voltage sags and swells.

Standby power supply with load-current harmonics neutralizer This technology combines the features of a standby power supply (SPS), which offers backup power in the event of an outage, with the ability to neutralize current harmonics. It is intended for use with advanced medical equipment and other critical loads that generate current harmonics, which can overload branch and neutral conductor wiring. Since the SPS provides load power only on demand, it is more efficient than an on-line uninterruptible power supply, through which current is continuously flowing.

Static VAR compensator Static VAR compensators (SVCs), which regulate voltage and power factor, have been on the market for a number of years. But EPRI is working on an advanced SVC that employs power electronics to continually correct voltage and power factor. Applicable in both utility and industry environments, the advanced SVC will be able to maintain capacitive output even when voltage is reduced to 15% of the normal voltage. By comparison, the output of conventional SVCs decreases as voltage decreases—and much more rapidly.

Solid-state current limiter/circuit breaker This technology will fulfill a role similar to that of conventional, electromechanical circuit breakers on the utility system. However, its advanced power electronics will allow utilities to switch feeders and clear faults much more quickly. The device can be used in conjunction with a utility's electromechanical breakers, since it will automatically limit the short-circuit current to a level within the capability of the existing equipment. □

The pressure is on

Standards organizations like IEEE and the International Electrotechnical Commission (IEC) are already beginning to set more stringent requirements for power quality. At the moment, there are a number of standards under development that would help alleviate power quality problems at the design level. Of particular interest is the revised version of IEEE 519-81, which would set recommended limits on the amount of total harmonic distortion generated by customers as well as utilities. The revision has been submitted to IEEE members for balloting. Also, the American National Standards Institute's ANSI/IEEE C62.41-1991, which is expected to be published this summer, recommends that manufacturers test their equipment for five types of surges. This recommended practice is an upgrade of ANSI/IEEE C62.41-1980 (previously known as IEEE 587), which specified testing for only two types of surges.

At this time, though, manufacturers are more preoccupied with international standards. The IEC standards, set by European countries, promise to be even more stringent than IEEE standards. In particular, the proposed IEC 555-2 would set very tight limits on harmonics. The new standards were initially intended to go into effect with the establishment of the European Community in 1992, but now their implementation is expected to be postponed until 1995. As John Roberts, a power standards authority at IBM, points out, the implications for any U.S. manufacturer who sells electronic goods overseas are severe: any equipment that does not meet the IEC standards will simply not be allowed into European countries.

Certainly it will cost companies something to build more protection into their products. Roberts estimates that the changes needed to comply with the new international standards would increase the cost of power supplies in computers by 20–30%. The expense would be passed on to consumers. "I think that we as manufacturers don't object to improving our equipment so we don't have such high harmonic currents. But it has to be done over a reasonable period of time," says Roberts, who is chairman of the power subcommittee of the Computer Business Equipment Manufacturers Association. "We want to know what limits to design to, and we want the time to do that." Roberts is among those who have sat on IEC committees to communicate manufacturers' concerns.

Back home in the United States, another standards body, the Underwriters Laboratories (UL), also is getting serious about power quality. Some UL testing pertaining to power quality has been conducted for a number of years. For instance, UL has performed overvoltage and undervoltage tests to determine how equipment will fare under such conditions. But a new initiative in power quality testing, specifically pertaining to harmonic distortion, just got under way in the past year. As part of this initiative, UL has established ratings on power transformers to ensure that a transformer will work safely and not overheat when a certain amount of nonlinear load is connected to it. While UL certification is not legally required for products introduced to the market, users often seek out the UL label, which indicates that a product meets a minimum standard for safety.

"Power quality has become quite an issue here in recent years," says Dave Dini, who is coordinating UL's research on power quality issues. "Power quality and safety go hand in hand, and power quality problems like harmonic distortion definitely have an impact on electrical safety." Dini expects UL's power quality testing to increase. Among the proposals being considered is one that would put limits on the amount of output voltage distortion allowed for UPS equipment. Research in this area continues.

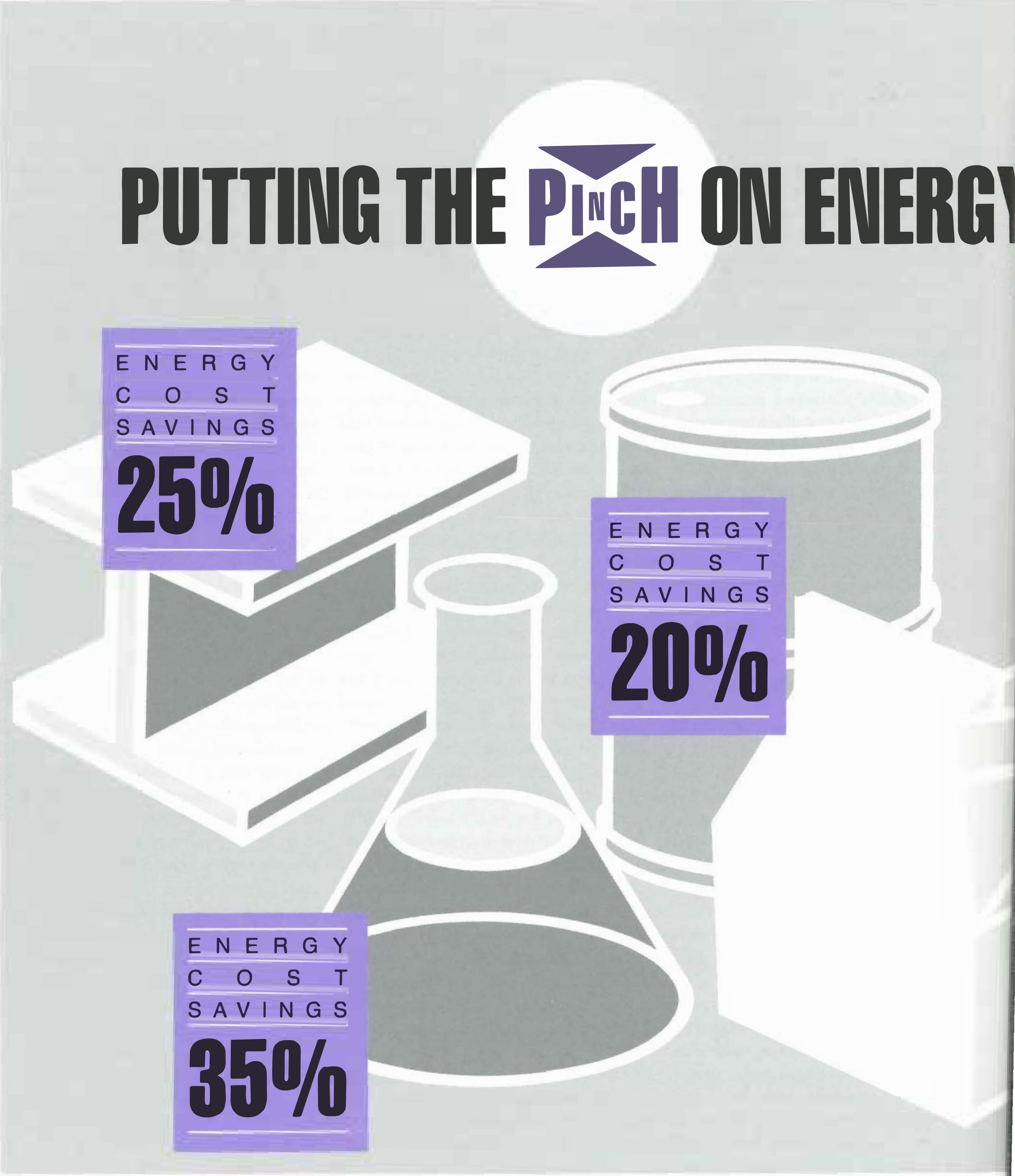
But standards alone don't induce manufacturers to build protective devices into their equipment. Like anyone else in business, the manufacturer is interested in pleasing its customers. As Don Staffiere of Digital, chairman of the R&D committee of the Power Sources Manufacturers Association, puts it, "We don't have any choice. If there's a glitch in the power line and my computer is going down, my customer is not going to be very happy with that." Describing manufacturers as "anxious to understand the issues so that we can help solve them," Staffiere says some have experienced frustration in trying to obtain data resulting from power quality studies. He stresses the need for better communication between utilities and manufacturers.

That kind of collaboration is exactly what PQTF and the power quality network are after. "Everybody wants this to happen and EPRI is trying to catalyze it," Key says. "Manufacturers want to make their equipment more compatible, and the utility industry wants to help them by explaining its environment, running tests, and suggesting modifications to their designs." But no matter how successful these and other efforts are, the power quality issue is not likely to disappear soon.

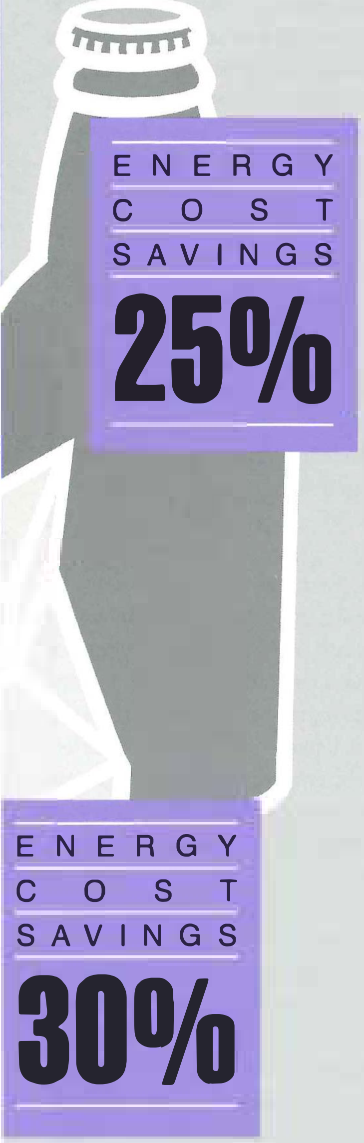
Says Smith, "Somebody asked me how to go about curing all power quality problems. I told him, 'We're going to take everybody out of their homes and stick them back in caves.' Technology is advancing, and it continues to carry with it new sensitivities. We're probably at the point where 35–40% of all electric power flows through electronic devices. This is supposed to increase to 60% by the year 2000." Nevertheless, EPRI's experts are confident that the Institute's work will keep the industry one step ahead of these problems. As Smith describes it, "The power quality machine is in place and the wheels are rolling."

This article was written by Leslie Lamarre. Background information was provided by William M. Smith, Product Delivery Enhancement Office; Marek Samotyj, Customer Systems Division; and Harshad Mehta, Electrical Systems Division.

PUTTING THE PINCH ON ENERGY



COSTS



THE STORY IN BRIEF

From steelmaking to milk production, virtually all industrial processes require both heating and cooling of the process streams. One key to top efficiency is exchanging heat in the most effective way between components within the system, cutting the need for additional heating or cooling equipment to a minimum. But until recently, finding the best configuration for process equipment and heat exchangers has been a complicated business —more of an art than a science. Pinch technology, a new energy analysis tool, now allows design engineers to track the heat flow from all the process streams in a system and identify modifications that can cut energy costs by 20–40%, often significantly reducing emissions and capital costs in the bargain.

As the demand for greater energy efficiency increases, a growing number of industries are getting back to basics—taking a fresh look at the fundamental design of their process plants. And thanks to an innovative new tool called pinch technology, many are discovering unexpected opportunities for significant efficiency improvements at relatively low capital cost.

"Despite its name, pinch technology is really more a technique than a technology—an analytical tool that allows design engineers to identify the optimal potential for heat exchange within a process plant," explains Ammi Amarnath, a senior project manager in EPRI's Industrial Program. Whether a plant makes plastic bags out of petroleum or beer from malt, most of the energy goes either to heat or to cool the various processing fluids involved. When one process stream needs to be heated and another cooled, engineers have typically tried to save energy through heat exchange between the two process streams.

That concept may sound simple enough. But in practice, identifying all opportunities for heat exchange, especially within a complex industrial plant that performs many different operations, isn't easy. Engineers have typically concentrated on heat exchange within individual production units, and they have had to rely as much on intuition as on skill in designing plants to take full advantage of heat exchange opportunities. Even when individual heat exchange units operate efficiently, they can add up to a poor overall process if they are linked together inappropriately. Moreover, in the past, design engineers had no way of knowing whether even a well-designed plant could operate at greater efficiency. "After all, there are many different ways in which the raw materials of a process can be prepared and combined, and different ways in which processes can be heated and cooled," Amarnath points out.

Nor is optimal energy efficiency a simple matter. "In plant design, there is always a trade-off between energy costs and the capital costs of heat exchangers and other equipment required to optimize energy efficiency," Amarnath notes. "We may be able to achieve very high energy efficiency—but with huge heat exchanger costs. And vice versa: eliminating some heat exchangers may help lower capital costs, but it will also reduce overall energy efficiency."

That's where pinch analysis comes in. "Pinch analysis allows engineers to determine the optimal energy efficiency that can be achieved by taking advantage of all opportunities for heat exchange," Amarnath explains. It also provides an easy way to analyze the trade-offs of capital cost and energy efficiency. The term *pinch* refers to a key system temperature constraint, the process pinch point, which thermodynamically limits the heat recovery and thermal energy efficiency possible.

To conduct a pinch analysis, engineers first calculate all the heating and cooling requirements of a process and then determine from those data the minimum amount of energy required if all opportunities for heat exchange are exploited. The analysis sets a target for optimal energy efficiency and also suggests ways to achieve that target through structural changes in plant process design. Ideally, the technique can provide the means to link all the unit operations within a plant, integrating the various chemical reactions and heating and cooling requirements in a way that makes the most efficient use of the available energy. It also provides a systematic way for design engineers to identify the most advantageous energy sources, based on the specific requirements of the processes involved.

"Too often, industries start with the given structure of the process plant and try to improve its energy efficiency through small modifications," explains Jim Kumana of Linnhoff March, a consulting firm that specializes in pinch analysis. "If we can go in and modify that structure to make the most efficient use of heat and power, we can usually achieve efficiency improvements that are 10 times as great."

Case studies in energy efficiency

As an increasing number of case studies show, the savings can be dramatic. At Champion International Corporation's pulp and paper plant in Cantonment, Florida, for instance, a pinch analysis sponsored by EPRI and Gulf Power demonstrated that energy efficiency could be significantly improved through several relatively simple modifications. The use of a heat pump could reduce reboiler duty by about 84%, and modification of the existing mill water system and the boiler feedwater heat exchanger systems could significantly enhance energy efficiency. In all, pinch analysis identified potential net fuel savings of 126 million Btu per hour of natural gas and 23 million Btu per hour of coal at the plant—totaling energy savings of more than $2 million a year. Even more impressive, those energy savings would be enough to pay back the capital cost of implementing the design changes in little more than a year and a half.

The Champion International case study is just one of dozens that attest to the potential benefits of "putting the pinch" on energy costs. Over the past several years, EPRI and its member utilities have sponsored 14 similar case studies in a variety of industries, including chemical plants, food processing plants, oil refineries, pulp and paper mills, and textile plants. The purpose was to determine which energy efficiency modifications would be economic for different types of industries. Among the highlights of those studies:

- At the Champlin Refining Company in Corpus Christi, Texas, pinch analysis conducted in collaboration with Central Power & Light identified several relatively simple changes in design that could reap savings of close to $1 million a year in electricity and fuel costs.
- At a Steuben Foods, Inc., dairy prod-

ucts processing plant, pinch analysis in collaboration with the New York Power Authority identified a variety of design modifications—including an additional heat exchanger, a closed-cycle heat pump system, and the use of variable-speed motors—that could save $290,000 a year in energy costs. The payback time, based on net energy savings and excluding the cost of process integration study and design, would be only 1.4 years.

▫ Pinch analysis at Washington's Port Townsend Paper Corporation, with assistance from Bonneville Power Administration, identified ways to eliminate a process bottleneck, thereby cutting purchased fuel by more than 50%, saving the company $1 million a year in energy costs, and reducing both NO_x and SO_2 emissions in the bargain—all with a recovery of capital costs in less than two years.

Over the past several years, the U.S. Department of Energy has also been conducting case studies using pinch technology. DOE's specific goal has been to identify economic industrial heat pump applications. Earlier this year, EPRI and DOE jointly sponsored a conference on industrial process integration in Houston, Texas, that provided an opportunity to evaluate the overall benefits and potential uses of pinch assessment.

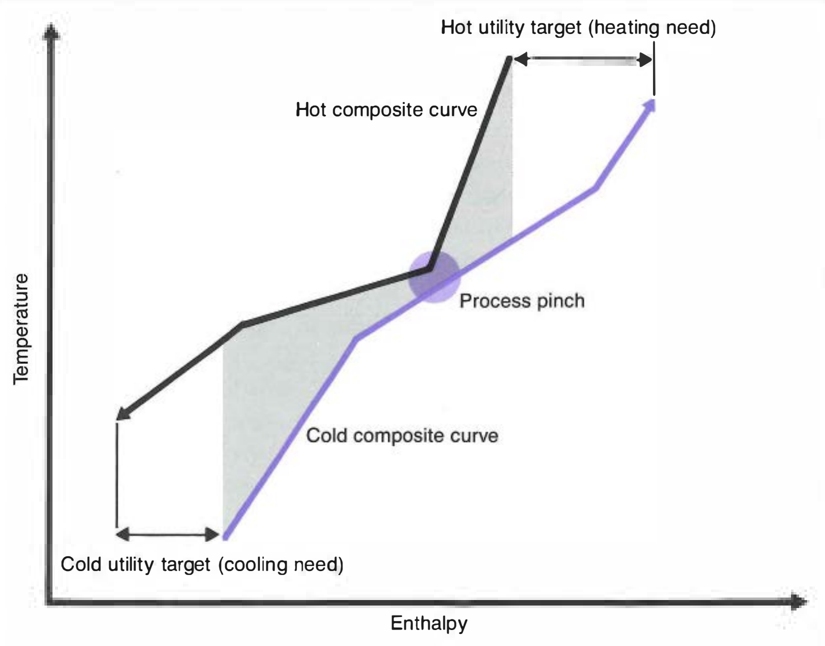
Among its 14 case studies, DOE reported six plants that are currently designing heat pump systems and improved heat exchange networks expected to yield energy savings ranging from $245,000 a year to more than $1.4 million. Payback times for the six projects ranged from just under three years to less than one year, with an average of 1.6 years. EPRI's case studies indicated energy savings ranging from $31,000 a year to well over $4 million, with an average payback

Plotting the Pinch

In any industrial process, streams of materials must be heated and cooled as raw materials are transformed into final products. The first step in pinch analysis is to combine the temperature characteristics for all the streams that need to be heated (called cold streams) into a single cold composite curve, and to combine those for the streams that need to be cooled (hot streams) into a hot composite curve.

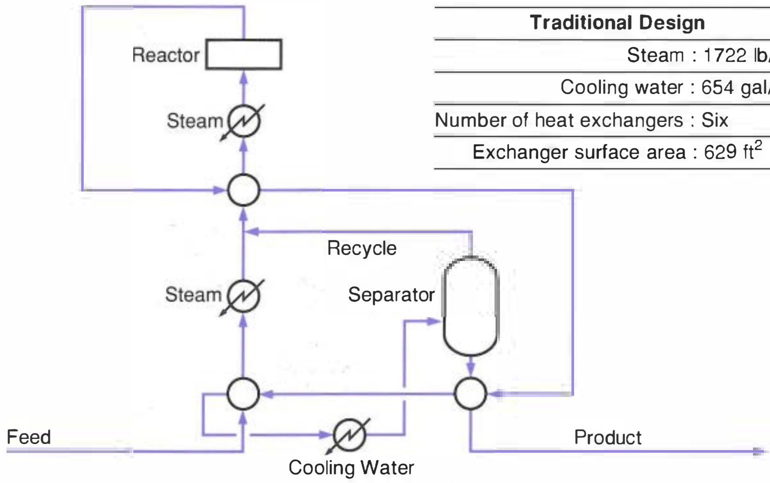
When both curves are plotted in a temperature-enthalpy diagram, the resulting graph vividly illustrates the optimal target for overall energy efficiency. The shaded region between the two composite curves indicates the potential for passive heat exchange between the hot and cold streams. The areas outside the shaded region represent process requirements that must be met by external heating and cooling utilities, such as steam and cooling water.

The point where the hot and cold composite curves are closest is called the process pinch; it separates the overall process system into a heat sink (above the pinch) and a heat source (below the pinch). To achieve optimal efficiency, the final process design must ensure that no cold utilities are used above the pinch and no hot utilities are used below. □



Pinch Technology at Work

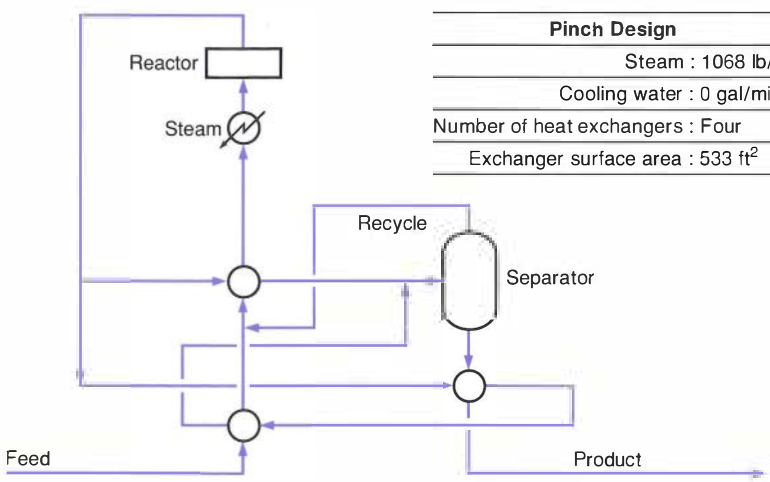
Traditional Design
Steam : 1722 lb/h
Cooling water : 654 gal/min
Number of heat exchangers : Six
Exchanger surface area : 629 ft^2



Imagine a simple industrial process that converts a raw material into a finished product by using two pieces of process equipment: a reactor and a separator. Heat exchange between hot and cold process streams meets some of the heating and cooling requirements, and the rest are met by steam heaters and a water cooler. A typical design that might be arrived at by using traditional methods is both safe and relatively efficient. But is it the optimal design?

An alternative design for the same process, generated by pinch technology, uses the same process elements and converts the same amount of raw material into the same product. But because of revised process flow and improved heat recovery, the pinch design requires 38% less steam and needs no cooling water—doing away altogether with the need for a cooling tower. The new design uses four heat exchangers instead of six, reduces the total heat exchanger surface area requirements by 15%, and is cheaper to build and operate. □

Pinch Design
Steam : 1068 lb/h
Cooling water : 0 gal/min
Number of heat exchangers : Four
Exchanger surface area : 533 ft^2



time of about 1.5 years. Remarkably, the overall energy savings made possible through design modifications based on pinch analysis averaged between 25% and 40%.

Beyond energy savings

But energy savings tell only part of the story. Pinch technology also provides a useful way to help process plants reduce the environmental impact of their operations on both water and air. Implementing pinch assessment recommendations reduces the amount of energy consumed and fuel burned, thus reducing emissions levels. "The equation is simple," says Amarnath. "If you can reduce a plant's heat requirements, you can reduce the environmental impact of generating that heat."

Pinch analysis may also point out ways in which steam or water can be recycled within process operations, further reducing the waste streams associated with production. In some cases, modifications may allow plants to increase capacity while maintaining total discharge volume at or below permit levels.

At a corn-milling plant in Decatur, Alabama, a DOE-sponsored case study identified heat pump applications and other design modifications that could reduce net source fuel by one-third, significantly cutting both NO_x and SO_2 emissions. Modifications suggested by the EPRI–Gulf Power pinch analysis at the Champion International plant could help reduce NO_x by 289 tons a year and SO_2 by 180 tons a year.

Pinch technology can also suggest ways to defer or avoid capital costs by revealing how to make the most efficient use of existing equipment. Because pinch optimizes process heat recovery, the heat and power systems in a plant can then be used for higher capacity. "If we can show a company how to make the most efficient use of a boiler system through the use of heat pumps or a new arrangement of heat exchangers," Amarnath explains, "the capital savings can be significant."

As the DOE case studies proved, pinch technology can also help industrial customers identify the most effective use of new technologies like heat pumps—thus speeding their acceptance and use. "In the past, heat pumps often proved uneconomical simply because they weren't placed correctly in the process," says Amarnath. "A pinch analysis can show not only whether a heat pump might improve efficiency, but exactly where it should be placed in the operation—and even the optimal size and type to use."

Moreover, the technique has proved particularly useful in identifying when cogeneration will provide economic advantages to large industrial customers—and when it will not. "When it comes to cogeneration, people seldom get it right," explains Linnhoff March's Jim Kumana. "Some plants may be generating too much of their own power. Others may be missing economic opportunities for cogeneration. Pinch analysis can be used to pinpoint the most efficient and cost-effective use of cogeneration."

In many instances, in fact, the benefits of cogeneration disappear as a result of the dramatic improvements in thermodynamic efficiency made possible by pinch assessment. When one of its large industrial customers was considering installing a 9-MW cogeneration system to cut costs, one utility used pinch analysis to identify better ways to conserve energy, including process designs that would recover waste heat and recycle 50% of the wastewater. "In that sense, the design modifications identified by pinch technology can be seen as an important alternative to cogeneration," says EPRI's Amarnath, who believes pinch analysis will become an increasingly important demand-side management tool.

"But regardless of whether pinch analysis supports or discourages the use of cogeneration," Amarnath insists, "it helps provide utilities with a full understanding of customers' heat and power needs and options—an understanding that could foster a better relationship between utilities and their large industrial customers."

Case Study Results

Company	Host Utility	Annual Energy Savings	Payback (years)
Champlin Refining	Central Power & Light	$839,000	1.2
Hoechst Celanese Fiber	Duke Power	$3,742,000	2.4
Champion International Paper	Gulf Power	$2,300,000	2.0
Port Townsend Paper	Bonneville Power Administration	$1,000,000	1.7
Steuben Foods	New York Power Authority	$282,000	1.3

A wide spectrum of applications

The scope and costs of a pinch analysis vary widely, depending on the complexity of the process plant and its objectives. Some large industrial firms, such as Exxon, and engineering companies, such as M. W. Kellogg, have developed in-house capability to perform pinch technology analysis. Smaller companies with only a few large integrated plants are more likely to hire outside consultants, whose fees can range from $10,000 to $100,000 or more.

To encourage cooperative activities between utilities and their industrial customers, EPRI has developed a primer on pinch technology (CU-6775), as well as guidelines for the use of heat pumps in a variety of processes (EM-3656, EM-4693, EM-4694). EPRI also continues to work in collaboration with member utilities to sponsor case studies in a variety of industries.

Perhaps the most impressive advantage of pinch analysis to be demonstrated by those studies is its flexibility. "Pinch technology can be applied to any plant that uses energy for heating and cooling, no matter what specific processes are involved," explains Paul Tripathi, president of TENSA Services, which has carried out a variety of pinch assessments under EPRI contract. "The EPRI and DOE case studies, for instance, represent a complete cross section of processing industries, from refineries and petrochemical plants to food, pharmaceutical, and pulp and paper plants." Pinch technology has even been used to improve the energy efficiency of naval vessels—allowing them to remain at sea for longer periods.

The technique's usefulness across a broad range of applications has important implications for utilities, which often work with customers from many diverse industries. "There's no way utility personnel can understand the many different industries and processes in their service territory," Amarnath points out. "Pinch analysis provides a consistent way to analyze system interactions that are applicable to any process, regardless of the specifics."

Pinch analysis can be done even before the foundation of a new industrial plant is laid, according to Tripathi, in order to build optimal energy efficiency into the process design. "By now," he points out, "most major contractors are aware of the important advantages of pinch. Experience has shown that correct integration in basic design not only lowers capital costs and saves energy but also makes plants

A Wealth of Opportunities

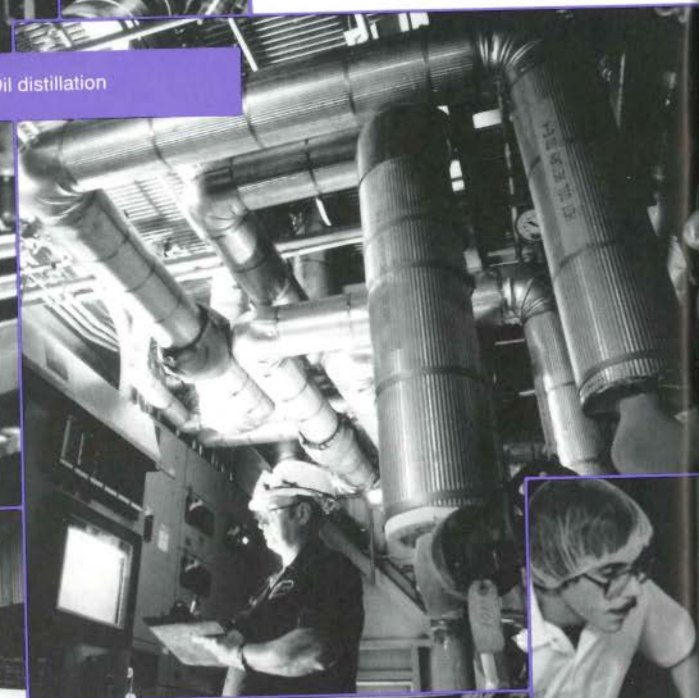
The pinch approach to optimizing heat exchange is applicable to virtually any industrial process that involves heating and cooling of materials. Reconfiguring production processes according to pinch analysis results can typically reduce energy costs by 20–40%.

Fiber production

Goodyear News Bureau

Brewing

T. Kawalerski/Image Bank

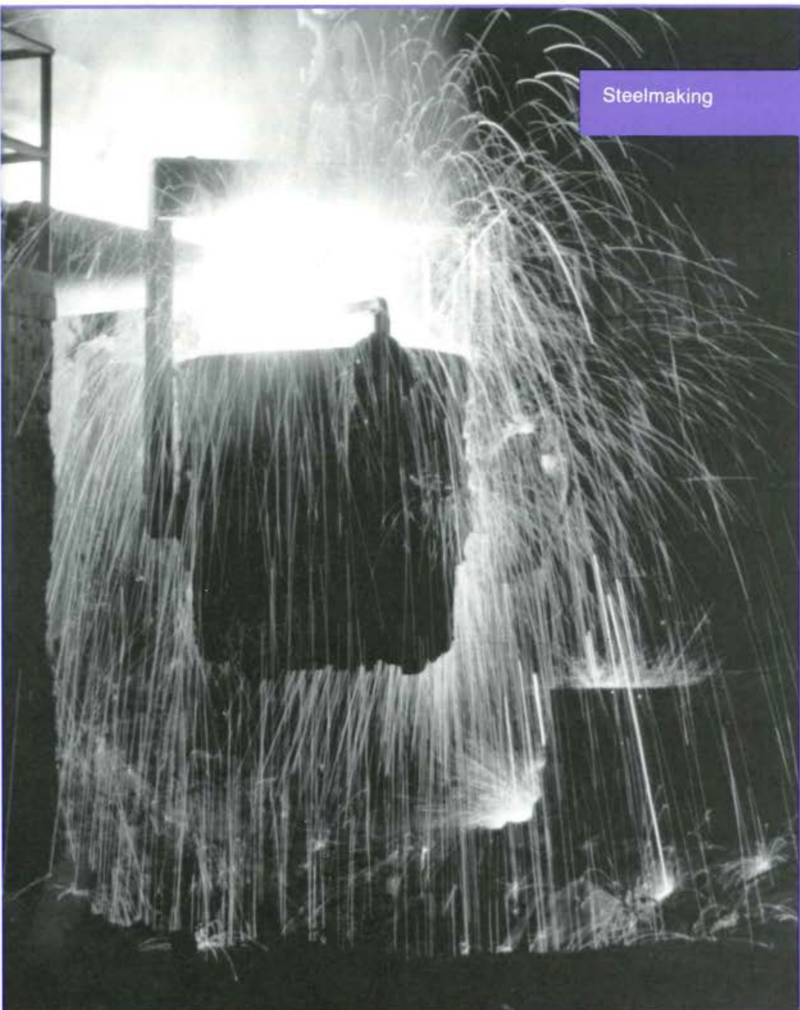


Oil distillation

T. Anderson/Pennsylvania Power & Light

Paper manufacturing

Ron May



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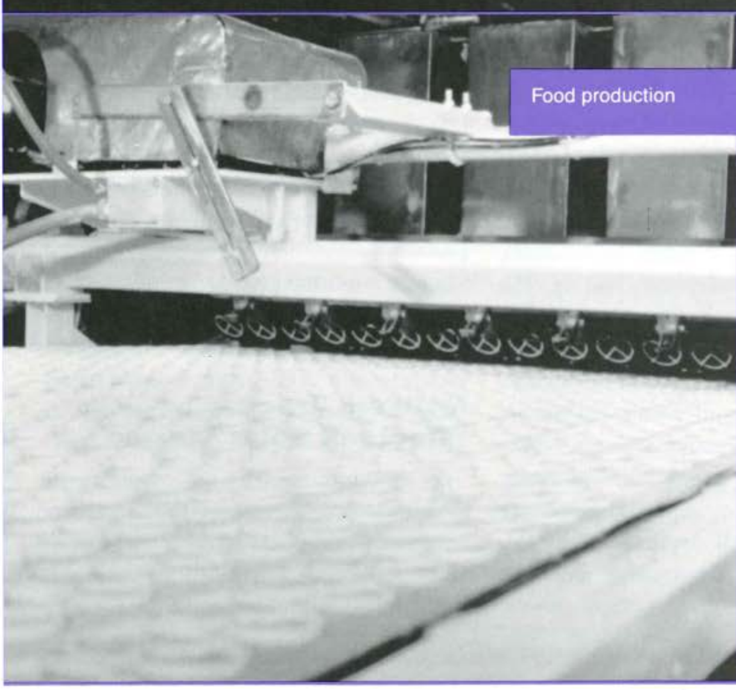


Ron May

more flexible in responding to ever-changing demands in the marketplace."

And as the EPRI and DOE studies have proved, pinch technology can also identify opportunities for redesign that lead to dramatic energy savings, even in plants that have already been "optimized" for energy efficiency through other means. Indeed, some of the most dramatic energy efficiency improvements have been identified in well-established plants. "In older plants, energy efficiency may not even have been a consideration when they were first designed," Amarnath notes. "Plant design may have been dictated instead by the need to keep capital costs low. Even where energy costs are a factor, many plants have been expanded over time, resulting in a lack of process integration among the different units."

In one case, an orange juice concentration plant set out to lower costs by replacing its 15-year-old evaporator with a new, more efficient model, which was expected to reduce energy consumption by 20%. Instead, the new evaporator's higher temperature added load to the refrigeration unit located elsewhere in the plant, thus offsetting the energy savings. Using pinch technology, design engineers would have been able to look at the entire plant as a single, integrated whole. Indeed, by going back to fundamental process data—thus avoiding any assumptions or preconceptions about what the design *should* look like—pinch analysis can give engineers a fresh look at the big picture.

"Pinch analysis not only sets a target for optimal energy efficiency, it also helps generate ideas for process changes that can achieve those targets," explains EPRI's Amarnath. "Pinch can help us identify possibilities for efficiency improvements that, using traditional design techniques, we might simply never have seen." ■

This article was written by Peter Jaret. Technical information was provided by Ammi Amarnath, Customer Systems Division.

TECH TRANSFER NEWS

Powering the Future in Charlotte

Three key EPRI Nuclear Power Division program activities are relocating from Palo Alto to the Institute's Nondestructive Evaluation (NDE) Center in Charlotte, North Carolina, to better serve clients among operations personnel at member nuclear power plants. The activities moving are the Nuclear Maintenance Applications Center (NMAC), the Plant Support Engineering (PSE) group's replacement parts engineering and materials management activity, and the Performance Demonstration Initiative, a new program for implementing ASME code requirements in the inspection of primary-system components.

The move, endorsed by the Nuclear Power Division Advisory Committee last January, is being carried out largely this summer and is expected to be completed by the end of the year. About six EPRI professional staff are moving to Charlotte, and another six are expected to be hired locally, according to Warren Bilanin, senior program manager.

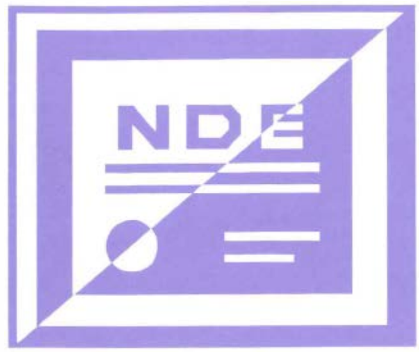
Noting nuclear utilities' growing reliance on EPRI for hands-on training and plant support services, Bilanin says the move is aimed at putting EPRI specialists closer to clients and making EPRI training workshops easier and less expensive for utility personnel to attend. Charlotte was chosen for the same reason it was chosen as the site of the NDE Center over a decade ago.

"If you look at a map of our member utilities' operating nuclear plants, you'll see that Charlotte is within a couple hundred miles of the geographic center of them," says Bilanin. "By moving the programs that are geared to hands-on work and training with plant operating staffs closer to the plants, we expect to achieve big savings in travel cost and time, for us as well as for the utilities. EPRI will be able to respond to utilities' needs for assistance quicker—often the same day the call comes in.

"By relocating these functions, EPRI is making a commitment to get more involved with utilities in keeping plants running safely and reliably while controlling nuclear operation and maintenance costs," explains Bilanin.

NMAC provides an international forum for technical support on nuclear plant maintenance issues through publications, workshops, and a telephone hotline. The center has produced over 15 technical guides on such priority issues as bolting practices, fuel oil handling, motor-operated valves, and freeze-sealing of piping. Its products and services reflect the collective insight gained from extensive operating plant experience and are designed to save utilities time and money while minimizing the risk of errors in plant maintenance.

PSE, formerly NCIG, is focused on reviewing practices and developing guidance for utilities in replacement parts engineering and related information management, including procedures for re-



ceipt inspection of replacement parts and for dedicating parts for safety-related service. The Performance Demonstration Initiative is largely devoted to the use of full-scale component mock-ups for demonstrating the capabilities of equipment, procedures, and personnel in the inspection of primary-system vessels, piping, and bolting.

"Utilities are increasingly tapping EPRI's capabilities in resolving issues and providing a forum for exchange of utility experience in the areas of maintenance, procurement, and inspection work," adds Bilanin. "As utilities look to the next generation of light water reactors, they are increasingly recognizing the need to share their experience in plant operation and incorporate that experience in future plants." ■ *EPRI Contact: Warren Bilanin, (704) 547-6123*

Network Tracks Effects of Solar Storms

A growing network of monitors for detecting geomagnetically induced currents from solar storms was in place and operating at five utility substations in time to record highly useful data during several recent series of geomagnetic disturbances that began in late March. The SUNBURST network of current recorders had been deployed on key substation transformers earlier this year under an EPRI-sponsored proof-of-concept study of their ability to relate geomagnetic currents to effects on utility power systems.

Scientists say this year's storms are some of the most severe in many years. Over a two-day period in late March, the North American continent experienced the strongest geomagnetic disturbances since 1989. Additional, milder disturbances followed in late April, with another series of storms in early June.

During solar storms, enormous flares of energy on the sun's surface hurl dense waves of protons and electrons through space. The charged particles reach the earth several days later, interacting with and shifting the earth's magnetic field, which in turn induces large currents that circulate in the earth and can enter power systems and overheat and damage equipment.

Data from one of the SUNBURST units, at the Chester static VAR compensator (SVC) substation in north central Maine, suggests that the severity of magnetic storms locally may differ from what is indicated by the planetary index issued by the National Oceanic and Atmospheric Administration (NOAA). The effects of a locally strong solar storm on April 28 were observed to be greater than the effects recorded during previously monitored events for which NOAA had reported the same moderate storm levels on the planetary index. Further investigation of the event disclosed that an Air Force magnetometer 100 miles northeast of the substation had recorded a storm two levels above the planetary index for that period.

The SUNBURST monitors continuously record levels of dc, ac, and harmonic currents at the utility transformer neutrals, as well as harmonics in the phase currents. According to Joseph Porter, project manager in EPRI's Electrical Systems Division, detection of dc indicates the presence of geomagnetically induced current (GIC), while the harmonic currents can be analyzed to determine the degree of transformer saturation and, therefore, potential damage to the transformer or other system elements.

During the March storm series, four operating SUNBURST units—in north central Maine, southeastern New York, central New Jersey, and central Maryland—all recorded maximum dc currents in transformer neutrals within about one minute of each other, consistent with the predicted sudden, continent-wide onset phenomena associated with very large solar storms. "While the event suggested that a SUNBURST network could not be used as a reliable advance warning system for GIC, it did demonstrate the value of the extensive data collected by the units in postevent analysis and troubleshooting," notes William Feero, president of Electric Research & Management, the firm that developed the monitors and operates the network for EPRI.

At the height of a March 24 storm, a filter bank at the Chester SVC substation tripped on overload, sending conflicting status reports to system operators and causing them to take the substation offline. Later analysis of the SUNBURST monitoring data helped identify a fault in system control hardware and gave the operators the confidence to quickly return the substation to service. At the substation in southeastern New York where a SUNBURST unit was installed, the collected data may provide the first hard evidence of the cause of three recent transformer failures. The data suggest that fairly low levels of GIC may nonetheless hold a transformer in deep saturation that could lead to failure.

"If the data collected on the existence of GIC in a transformer and on its ability to cause sustained saturation are correlated with transformer failure history at that substation, then mitigation steps may be required," says Feero. "At present, few utilities take specific actions to protect against transformer failure during a geomagnetic disturbance.

"The data also suggest—and this is of critical importance to the reliability of the eastern grid—that baseload generating plants sited at the boundaries of igneous rock structures in the earth's crust are at risk from GIC. Since the only mitigation practiced to date at a few plants has been to back off baseload units to 80%, a geomagnetic disturbance during a peak load period would have a serious impact on system reserve."

After observing the level of GIC at its SUNBURST site, one utility involved in the EPRI pilot study has ordered two permanent installations. Several other utilities in the United States and Canada have also ordered or are considering SUNBURST units for installation at key transmission locations. The greater the number of points in the monitoring network, the more data engineers will have for piecing together the clues from the next wave of solar storms. For product information or ordering, call Electric Research & Management, (814) 466-3031. ■ *EPRI Contact: Joseph Porter, (202) 872-9222*

Air Quality Control

Pulse-Jet Baghouses for Utility Applications

by Ramsay Chang, Generation and Storage Division

ABSTRACT *Recent technological developments suggest that pulse-jet-cleaned fabric filters have the potential to become the next-generation particulate control technology for the U.S. utility industry. Their small size and modular design offer capital cost savings of up to 40% in comparison with the reverse-gas baghouses commonly used by U.S. utilities. A new EPRI-developed hybrid design combining an electrostatic precipitator and a pulse-jet baghouse is especially attractive for use in existing plants that need performance upgrades. Compared with alternative particulate control options, the new design could save a utility up to 70% in capital costs.*

The Clean Air Act Amendments of 1990 require utilities to reduce sulfur dioxide (SO_2) emissions significantly. Certain approaches that could be cost-effective for specific sites, such as fuel switching and sorbent injection, can severely affect the particulate collection performance of existing electrostatic precipitators. Pulse-jet baghouses—because of their compactness and their ability to meet stringent particulate emissions limits regardless of variations in coal type or fly ash properties—are an attractive upgrade option for underperforming precipitators. These baghouses are also a very promising option for compliance with possible future emissions regulations on fine particulates and air toxics.

Pulse-jet baghouses are distinguished by their use of periodic short, powerful bursts of air to clean the bags. This energetic cleaning allows a pulse-jet baghouse to operate at two or more times the filtration velocity (as measured by the ratio of airflow to bag surface area, or air-to-cloth ratio) of a conventional reverse-gas-cleaned baghouse, without any increase in pressure drop. To function in this fashion, the bags are supported by metal cages and suspended from a tubesheet, with ash collected on the outside of the bags (Figure 1). Because bags can be removed from the top, there is no need for walkways between them, and they can be packed closely in each compartment. Thus pulse-jet baghouses have about half the footprint of reverse-gas baghouses, an important consideration for sites with limited space. Moreover, compartments often can remain on-line while the bags are being cleaned, thereby eliminating the need for a spare compartment to handle this flow.

In 1988, EPRI began a systematic assessment of pulse-jet baghouse technology through a worldwide survey of current users, studies of pilot baghouses, and economic analyses (RP3083). The results to date confirm the benefits of pulse-jet baghouses for U.S. utility applications.

Current user experience

Pulse-jet baghouses are used widely in industrial applications in the United States and abroad, as well as by utilities abroad. Early pulse-jet baghouses were generally used with small industrial boilers and had fairly short bags (8 to 12 ft) made of woven fiberglass. The units were designed to operate at air-to-cloth ratios as high as 6 ft/min. Under these conditions, performance was inconsistent. For example, some units had bags that lasted up to three to four years, but quite a few other units were plagued by much shorter bag life, high pressure drop, and high opacities.

Recent advances in design and bag filter materials have greatly improved the reliability and performance of pulse-jet baghouses, leading to their successful use at increasingly larger installations. In Australia, for example, one 500-MW unit and two 350-MW units have recently come on-line, and two 500-MW units are under construction. In Europe, several units ranging from 200 to 350 MW have been constructed.

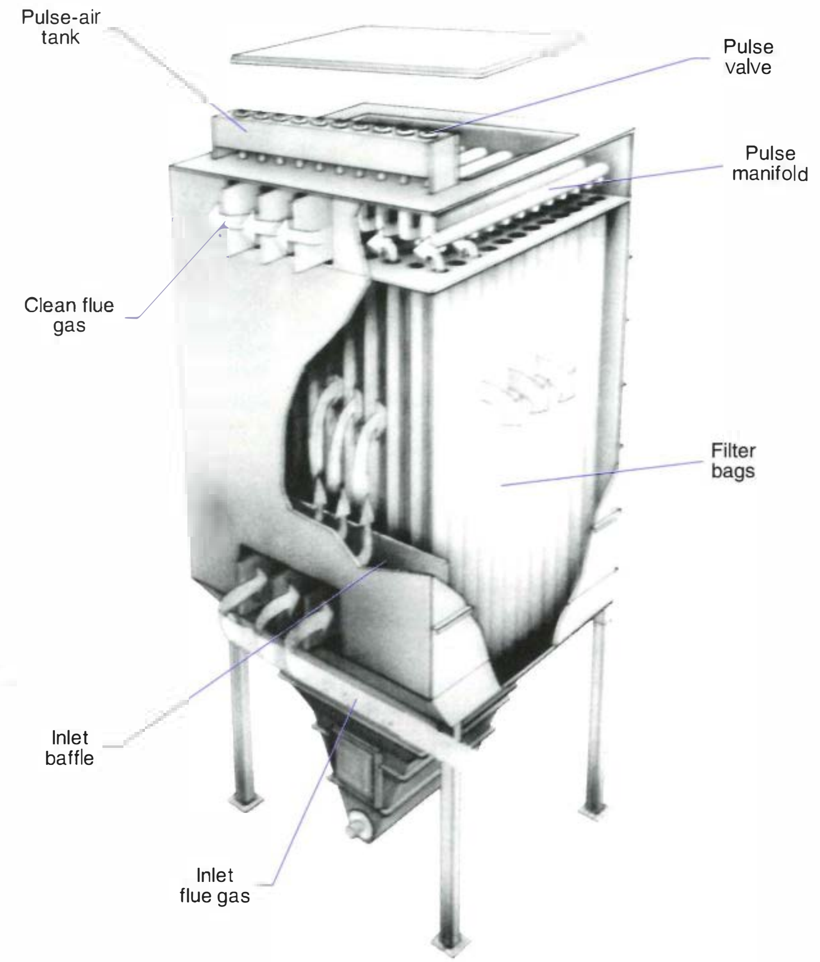
One major advance has been the introduction of synthetic felts, such as Nomex, Ryton, P84, Dralon-T, and Tefaire, for baghouse applications. These felts are highly efficient filters and generally resist abrasion better than glass fabrics. In addition, there have been improvements in the pulse-air cleaning system, cage design, and gas distribution. EPRI's survey of recent experience with units using synthetic felts and improved baghouse designs found that they have collection efficiencies similar to those of reverse-gas baghouses, easily holding outlet emissions below the New Source Performance Standard of 0.03 lb/10^6 Btu. In fact, 35% of the baghouses surveyed had outlet emissions below 0.01 lb/10^6 Btu. The survey also showed that an average flange-to-flange pressure drop of about 6 in. of water can be expected at an air-to-cloth ratio of 4 ft/min. This pressure drop is similar to that in reverse-gas baghouses, which operate at air-to-cloth ratios of 1.5–2 ft/min.

While woven glass fabrics generally were found to be more fragile and to produce greater pressure drops than felts, some users reported good performance with heavyweight fiberglass bags. However, these bags are generally operated at a conservative air-to-cloth ratio (e.g., 3 ft/min), used with carefully designed cages, and installed with special care to avoid localized abrasion. Since woven glass is significantly cheaper than many of the felts and generally has higher temperature capabilities, it may be suitable for some utility applications—as long as its limitations are carefully considered in designing the baghouse.

Recent advances also make it possible to use filter bags 20 ft or more in length; one design uses 26-ft bags. These longer bags make pulse-jet baghouses even more space-efficient, opening up the possibility of direct retrofits into fairly small precipitator casings. A recent EPRI study showed that a pulse-jet baghouse with 20-ft-long filter bags could fit into a precipitator whose specific collection area (SCA) is about 275–350 $ft^2/10^3$ acfm (at 9-in. plate spacing). Such retrofits have already been demonstrated commercially in Australia and Europe. At the Munmorah station of the Electricity Commission of New South Wales, two 350-MW electrostatic precipitators were converted to pulse-jet baghouses. The first has been in operation since August 1988 without any bag failures and with outlet emissions below 0.01 lb/10^6 Btu. And in Europe, several precipitators have been successfully converted into pulse-jet baghouses.

One concern expressed by potential users of pulse-jet baghouses is that operation and maintenance requirements will increase because of short bag life and the greater number of components, such as solenoids, diaphragm valves, and cages. EPRI's recent survey indicates that a properly selected felt in a well-designed and -operated baghouse should have a bag life of more than three years. Few of the installations surveyed have reported any problems with baghouse components.

Figure 1 In a pulse-jet baghouse, ash is collected on the outside of the bags, which are cleaned by short, powerful bursts of air. The compact, modular design and high efficiency of these baghouses make them an attractive retrofit option. Source: Fläkt Industri AB, Sweden.



Pilot studies

EPRI is conducting a pilot study program to evaluate pulse-jet baghouse performance specific to various U.S. utility fossil plant applications. In connection with this program, EPRI built or obtained four 1-MW pilot pulse-jet baghouses that can be easily transported from site to site. It also converted a 10-MW pilot reverse-gas baghouse at Gulf Power's Scholz plant into a pilot pulse-jet unit for use in parametric studies. The modified unit has compartments featuring the three common pulse-jet bag-cleaning designs, as well as a reverse-gas compartment. Finally, EPRI constructed a 4-MW pilot pulse-jet unit at its High-Sulfur Test Center (HSTC) for evaluation with various SO_2 control processes. All the units use full-scale components and 20-ft-long bags. Table 1 summarizes the pilot study program.

Table 1
PULSE-JET BAGHOUSE PILOT DEMONSTRATIONS

Host	Plant	Fuel/Other Conditions
Carolina Power & Light	H. F. Lee	Low-sulfur eastern coal; cycling plant
Colorado Springs Department of Utilities	Martin Drake	Low-sulfur western coal
Consolidated Edison of New York	Arthur Kill	Oil
Duke Power	Marshall	Low-sulfur eastern coal; Compact Hybrid Particulate Collector (COHPAC)
New York State Electric & Gas (EPRI High-Sulfur Test Center)	Kintigh	High-sulfur eastern coal; spray drying; Hybrid Pollution Abatement System (HYPAS)
Florida Power & Light	Sanford	Orimulsion (oil-water emulsion)
Gulf Power	Scholz	High-sulfur eastern coal; side-by-side comparison of three pulse-jet designs
Ohio Edison	To be determined	Medium-sulfur eastern coal
Public Service of Colorado	Comanche	Powder River Basin coal
Tennessee Valley Authority	Shawnee	High-sulfur eastern coal; sorbent injection; spray drying
TU Electric	Big Brown	Texas lignite; COHPAC

Studies at the Colorado Springs Department of Utilities, Consolidated Edison of New York, Carolina Power & Light (CP&L), and Florida Power & Light have been completed. Tests are in progress at TU Electric, the HSTC, and Gulf Power. Future test sites include Duke Power, the Tennessee Valley Authority, Public Service Company of Colorado, and Ohio Edison.

Results to date have been very positive. In all the tests, outlet emissions have been less than 0.01 lb/10^6 Btu, and tubesheet pressure drops could be maintained between 3 and 5 in. of water at air-to-cloth ratios of 4 ft/min.

At Colorado Springs, two fabrics were tested with a low-sulfur western coal for 2800 and 5070 hours, respectively. The Con Edison test featured an oil-fired unit, a new application for pulse-jet baghouses. With pulse cleaning once every 15 hours (on average), the pressure drop was maintained at about 3.5 in. of water through 2262 hours of operation. These results show that pulse-jet baghouses can collect oil fly ash effectively. The CP&L pilot unit was subjected to numerous shutdowns and startups, owing to the cycling operation of the plant and to several boiler tube leaks. Nevertheless, the unit operated for 1700 hours over a nine-month period without problems. The TU Electric system has been evaluated for 2000 hours on Texas lignite, while at Gulf Power's Scholz plant, one of the pulse-jet compartments has been operated for over 5500 hours on a high-sulfur eastern bituminous coal. Some bag failures, attributed to poor cage and filter bag fit, occurred during testing at Scholz. These failures underscore the importance of proper cage design and filter bag specification in maximizing bag life.

COHPAC

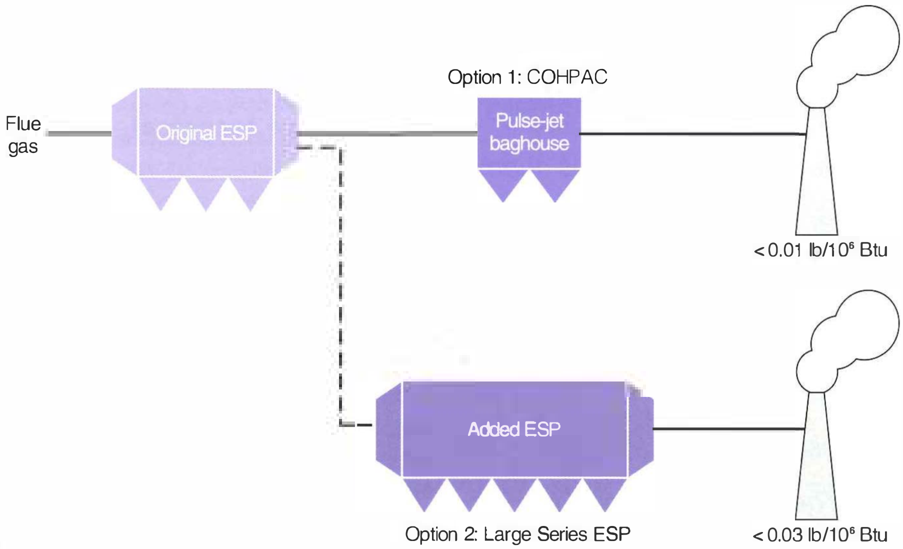
The Compact Hybrid Particulate Collector, or COHPAC, is a recent EPRI-developed and -patented concept that may be able to save up to 70% in space requirements and capital costs compared with conventional systems. The basic approach is to place a baghouse after a precipitator to serve as a polishing or performance-upgrading unit. Since the precipitator charges particles and removes a significant portion of them from the gas stream, the flue gas reaching the baghouse has a significantly reduced dust load; and those particles that remain may carry a residual electrostatic charge. As a result, the baghouse can operate at very high air-to-cloth ratios—16–20 ft/min versus 4 ft/min with a conventional, stand-alone pulse-jet baghouse—without an increase in pressure drop or emissions. Therefore, a COHPAC pulse-jet baghouse can be one-fourth the size of a normal pulse-jet baghouse or smaller.

Figure 2 shows an example of this approach. An electrostatic precipitator with an SCA as small as 150–200 $ft^2/10^3$ acfm is followed by a small pulse-jet baghouse in the COHPAC configuration (option 1) to hold outlet emissions at or below the limit of 0.03 lb/10^6 Btu. In contrast, if another precipitator were added to meet such a stringent limit (option 2), it might require an SCA of 300–800 $ft^2/10^3$ acfm. (The larger design would be needed for boilers burning low-sulfur coals or using dry sorbent for SO_2 control upstream of the precipitator.) A preliminary economic analysis of these two options for a specific utility site contemplating a precipitator upgrade has shown cost savings of up to $100 million for two 575-MW boilers by using the COHPAC configuration instead of adding precipitators.

One concern about COHPAC is the potential for the fine particles exiting a precipitator to "blind" the filter bags—that is, to penetrate the filter fabric and become lodged there—causing pressure drop to increase uncontrollably. With this in mind, the concept was tested at both bench and pilot scales. The bench tests were performed at EPRI's HSTC with fly ash exiting a precipitator at a rate of 0.1 lb/10^6 Btu. A small fabric swatch was operated at an air-to-cloth ratio of 20–25 ft/min, with periodic pulse cleaning. Because the average pressure drop could be maintained at 3.5 in. of water over 440 hours of testing, the results justified scale-up to a 1-MW pilot.

The larger COHPAC demonstration used the transportable pulse-jet baghouse at TU Electric's Big Brown station, which fires lignite. Here the tubesheet pressure drop remained stable at 6 in. of water at an air-to-cloth ratio of 18 ft/min over 2000 hours of testing, with outlet emissions of less than 0.003 lb/10^6 Btu. These promising results have prompted one utility to initiate a full-scale (160-MW) demonstration of the concept.

Figure 2 In a new EPRI-developed design called COHPAC, a pulse-jet baghouse is placed after a small electrostatic precipitator (specific collection area as low as 150–200 $ft^2/10^3$ acfm) to upgrade particulate collection performance. This hybrid configuration offers significant capital cost and space savings over the option of adding a second ESP, which would require an SCA of between 300 and 800 $ft^2/10^3$ acfm, depending on the fuel.



Future work

EPRI will continue to use the pilot baghouses to address performance issues specific to U.S. utility applications. Testing will include additional fossil fuels, fluidized-bed combustors, and spray drying and sorbent injection SO_2 control. Pulse-jet cleaning techniques will also be applied to advanced high-temperature processes using ceramic filter bags and candles; one promising process uses ceramic catalytic filter bags at 800°F with dry sorbent and ammonia injection for the combined control of SO_2, nitrogen oxides, and particulates. EPRI will assess long-term filter bag durability at selected sites by operating the pilot units continuously for one to two years. Also, it will pursue several approaches for optimizing COHPAC performance.

To address utility interest in the collection of air toxics by particulate control devices, the pilot and demonstration baghouse projects are closely coordinated with EPRI's PISCES (Power Plant Integrated Systems: Chemical Emissions Study) project. Using sampling and analysis protocols established under PISCES, researchers will measure emissions of suspected air toxics and will evaluate their control by the pulse-jet baghouses during the operational test programs.

With the increased understanding of pulse-jet baghouse design and operation derived from the current program, utilities have begun to show interest in full-scale applications and demonstrations. So far, six utilities are assessing potential applications, and two are pursuing preliminary engineering and economic analysis for specific sites, with possible full-scale demonstrations in 1992.

Plant Support Engineering

Evaluating Commercial-Grade Replacement Items

by Warren Bilanin, Nuclear Power Division

The decrease in nuclear power plant construction in the early 1980s caused many suppliers of parts and components to discontinue their quality assurance programs that supported qualification of nuclear-grade items. As a result, utilities operating nuclear plants had to assume the responsibility for evaluating requirements for replacement items, identifying commercial-grade equivalents, and reporting deficiencies in these parts. In the late 1970s and early 1980s, dozens of utilities operated nuclear plants, and every plant faced the need for thousands of replacement items over its lifetime. Clearly, a consistent way to identify, evaluate, and dedicate commercial-grade items (CGIs) for use in the nuclear industry was needed.

Three major requirements emerged from this situation, each of which called for a collaborative effort involving EPRI, utilities, and the appropriate vendors. First, as the number of suppliers able to provide identical replacement items decreased, plant engineers needed to identify parts equivalent to the original equipment. Second, a significant effort was necessary to evaluate and dedicate these commercial-grade replacements. And third, procurement controls were needed to guard against the infrequent attempt at substandard, or even fraudulent, parts supply. In response to these needs, the utility group NCIG, under EPRI sponsorship, developed a guideline to help utilities procure safety-related CGIs. This work is documented in EPRI report NP-5652, *Guideline for the Utilization of Commercial-Grade Items in Nuclear Safety-Related Applications (NCIG-07)*.

In implementing the NCIG-07 guideline, utilities discovered the need for a common ap-

ABSTRACT *A nuclear power plant uses thousands of replacement items during its lifetime. When many suppliers abandoned their quality assurance programs during the plant construction slowdown of the early 1980s, an EPRI-sponsored utility group called NCIG developed guidelines to help utilities evaluate replacement items themselves. However, the need became clear for greater collaboration. Thus EPRI established the Joint Utility Task Group (JUTG) to pool utilities' resources and develop criteria for dedicating commercial-grade items for safety-related nuclear applications. So far, the JUTG has developed a generic evaluation process and completed technical evaluations of 56 replacement items. The resulting information is available in an on-line database through EPRINET.*

proach to conducting technical evaluations, and together with EPRI, they initiated the development of a subsequent report—published as EPRI NP-6406, *Guidelines for the Technical Evaluation of Replacement Items in Nuclear Power Plants (NCIG-11)*. The two publications received an enthusiastic response from nuclear utility personnel. The NCIG-07 guideline received endorsement from the Nuclear Management and Resources Council, as well as conditional endorsement from the Nuclear Regulatory Commission (NRC) staff. The later NCIG-11 technical evaluation guidelines also received industry recognition as a viable resource.

However, implementing the processes in these guidelines has posed a sizable challenge. Since CGI technical evaluations can be difficult and costly to perform but result in much information that is easily shared and often has wide application, this area offered opportunities for further cooperative efforts.

In October 1989, EPRI initiated the Joint Utility Task Group (JUTG) to meet the challenge of efficiently implementing the published guidelines. Two subgroups were chartered: the Technical Work Group (TWG) performs technical evaluations of CGIs; the Technical Advisory Group (TAG) coordinates efforts and reviews the work to ensure its technical accuracy and analytical rigor. TWG members are plant-level procurement and process engineers who work with specific items on a daily basis and have access to data and process information. TAG members were selected for depth of experience in managing nuclear plants. The TAG acts as a management and steering committee, reviewing the information prepared by the TWG to ensure full implementation of the processes set out in the published guidelines. Consistency between the JUTG's activities and the published guidelines is further enhanced via a formal working relationship between the JUTG and NCIG. In addition, whenever the complexities of the technology require it, the two JUTG groups seek outside expertise.

The JUTG has prevented duplication of data gathering and analysis and has accelerated the completion of technical evaluations by pooling existing information. Also, joint survey coordination with the Nuclear Procurement Issues Committee has enhanced and streamlined communication with suppliers. Finally, to provide rapid access to constantly updated information, the JUTG has established the Commercial-Grade Items Database, available to all EPRI members through EPRINET™, the Institute's electronic communication network.

Performing a technical evaluation

The overall issue is to ensure equivalent quality and function in materials, parts, and components that replace original equipment in nuclear plants. Two NRC regulations bear on this topic. One (10CFR50 Appendix B) sets quality assurance standards for suppliers of nuclear-grade equipment, including replacement items. If a utility cannot find a supplier certified under this regulation, the other regulation (10CFR21) provides for items that meet the definition of commercial grade to be "dedicated" for use in the nuclear industry. The work of EPRI, NCIG, and the JUTG has clearly defined a process for this type of dedication.

One important caveat for the joint conduct of technical evaluations is to keep responsibility for equipment decisions in the hands of plant-level engineers. Beyond meeting the general criteria identified by the JUTG, the procurement process must take account of an item's specific application. For example, a fuse that protects an office air-conditioning system does not have to meet the same testing criteria that the fuse must meet to protect a feedwater pump circuit. Only on-site engineering can determine application-specific considerations for technical evaluations. The generic process discussed below is a resource that will expedite the final plant-unique application review.

The generic process for a technical evaluation (Figure 1) begins when the JUTG identifies a needed item. The Technical Work Group then gathers data on the item and applies the processes outlined in the NCIG-07 and -11 guidelines. The TWG lists critical characteristics for design of the item (such as form, fit, and function) and selects acceptance criteria to guide subsequent inspections and tests. For example, a fuse in a particular application must be able to carry a small specific amperage of overcurrent but blow immediately if the current spikes above a threshold level. In this case, acceptance criteria may include destructive testing of a predetermined number of sample fuses. A draft technical evaluation report for fuses would detail these characteristics and criteria.

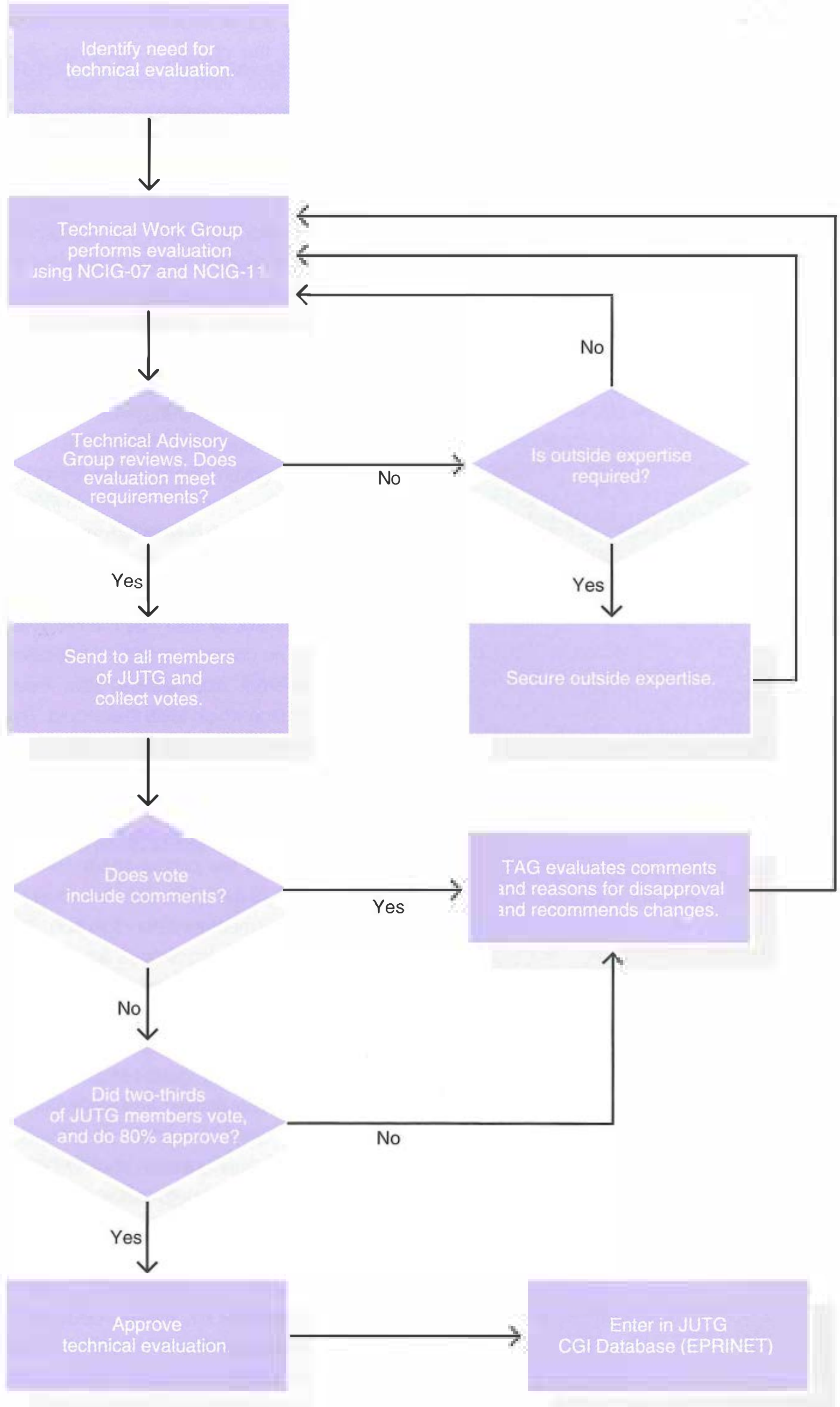
The TWG sends its draft technical evaluation to the Technical Advisory Group, which makes sure that the guidelines have been followed, that the chosen characteristics are indeed the critical ones, and that criteria for acceptance are realistic and complete. Once a final technical evaluation package is approved by the TAG, it goes to all JUTG member utilities for review. Each utility analyzes the technical evaluation and votes either approval, approval with comments, or disapproval with reasons. For an evaluation to be approved, two-thirds of the JUTG members must respond and 80% of the respondents must vote for approval. Otherwise, the TWG and the TAG must both review comments and reasons for disapproval and incorporate those that are appropriate. All comments that accompany JUTG ballots receive responses regardless of approval results. Once a technical evaluation is approved, it is entered into the CGI Database so that JUTG members have easy access to the information.

The JUTG effort addresses two major classes of issues to ensure equivalent quality in replacement parts and material in nuclear plants. One set of issues focuses on process: how to establish an operating consensus that accounts for all the complexities and technical detail necessary to ensure reliable information. The other set involves engineering issues: how to determine critical design characteristics and acceptance criteria. These two sets of issues are intertwined in the operation of the JUTG but are discussed separately here for simplicity.

Building consensus

The process issues the JUTG has tackled include establishing clear definitions, demonstrating the benefits of working together, identifying tasks that can be done in common, and selecting an approach that is feasible in practice. In all these issues, the JUTG has been

Figure 1 By establishing a generic process for evaluating commercial-grade replacement items for nuclear power plants, the Joint Utility Task Group (JUTG) has avoided duplication of effort and created a framework for information sharing among utilities. The procedure taps the expertise of plant-level engineers and operations managers and incorporates feedback from JUTG members.



ITEMS IN THE CGI DATABASE

- Ac/dc contactors
- Adhesives
- Bearings
- Capacitors
- Cement
- Compression fittings
- Concrete
- Conduit fittings
- Connecting wires
- Control and transfer switches
- Couplings
- Diodes
- Drive belts
- Electrical lugs: insulated
- Electrical lugs: uninsulated
- Expansion anchor bolts
- Fasteners: bolts (≥1/4 in.)
- Fasteners: flat washers
- Fasteners: lock washers, helical spring
- Fasteners: lock washers, tooth type
- Fasteners: nuts (≥1/4 in.)
- Fasteners: sheet metal tapping screws
- Filters
- Fuses: UL 198D
- Fuses: UL 198E
- Gaskets
- Governors
- Graphite packings
- Greases
- Grouting
- Industrial oils
- Integrated circuits
- Limit switches
- Machine screws
- Machine screw nuts
- Mechanical seals
- Molded-case circuit breakers
- Motors
- Motor/engine oils
- O-rings
- Overload heaters
- Pressure indicators
- Pressure switches
- Pump impellers
- Relays: control
- Relays: protective
- Resistors
- Solder
- Solenoid valves
- Structural steel
- Switching transistors
- Terminal blocks
- Test switches
- Transmitters
- Unistrut components
- Valves

aware of a key limitation: the final responsibility for meeting regulatory requirements rests with each utility, and no group consensus can relieve this responsibility.

The JUTG's first work with process issues was to clarify the phrase "dedication of a commercial-grade item," which had been open to an array of interpretations. According to federal regulation, a commercial-grade item meets three criteria: it is not subject to nuclear-unique requirements, it is used in common applications outside the nuclear industry, and it is available on the basis of published specifications. The dedication of such an item occurs when a utility formally decides to accept the item for a particular safety-related application. At the moment of the acceptance decision, deficiency reporting becomes the responsibility of the utility. But what criteria should govern the acceptance decision?

In practice, there are diverse approaches to the acceptance of CGIs. Because an organization cannot perform acceptance tests on every characteristic of every item it receives, and because no common standard has been available, different approaches have been used to determine which tests to conduct. The JUTG is addressing this problem by completing a technical evaluation for each specific item—from compression fittings to capacitors, from greases to gaskets. A technical evaluation defines the critical characteristics that the design of the particular item must include in order to meet its safety function. The technical evaluation also defines acceptance criteria for completing the item's dedication for safety-related service. But the question now becomes how the industry as a whole can bring consistency to the determination of critical design characteristics and acceptance criteria.

In response to this question, the JUTG has sought to demonstrate the benefits of working together. It has identified three key benefits. First, standardizing the technical evaluation of CGIs minimizes the financial impact on utilities that accept responsibility for CGI dedication. Second, cooperative efforts help ensure uniform regulatory compliance. Third, the quality of information available to each utility improves, increasing confidence and facilitating decision making. As more and more utilities have participated in the process, an added benefit has become apparent: the interchange of information has created leverage to accomplish a huge task and acted as an educational force within the industry.

The JUTG has also identified a set of common tasks. These include creating and using a common format for documenting technical evaluations; identifying a process for determining critical design characteristics; reviewing industry standards, specifications, and benchmarks for each type of CGI; and conducting joint manufacturer and supplier surveys. Another task that no utility could perform on its own is to develop an industrywide performance history for each CGI. The necessary data gathering and analysis can be accomplished only through communication and collaboration.

Finally, the JUTG needed to develop and follow a system that would be effective in actual practice, given the complexities of daily plant operation. Three responses to this need have emerged. The separate operation of the TWG and the TAG ensures dialogue between people at different professional levels within the JUTG, providing a reality check. Also, the technical evaluation approval method solicits and incorporates extensive comments, creating a dialogue among member utilities. And the development of an on-line database allows the dissemination of current information for practical application by participating utilities.

Resolving engineering issues

As process issues were clarified and research on CGIs gained momentum, technical evaluations were conducted. Information was compiled on a given type of CGI, and its design characteristics were identified. Then discussions led to the selection of the design characteristics critical to the item's safety-related function. Such discussions may focus on the familiar properties of simple electrical items like fuses or look at extremely complex components of engines, such as governors. Identifying critical design characteristics may be straightforward or may delve into narrow engineering fields. Achieving agreement on such issues depends on gaining access to and processing specialized information. For complex items not designed especially for the utility industry, consultation with technical experts from other fields may be necessary.

Items are typically subject to standards common to the industry that designs and manufactures them. For example, electrical items may be subject to requirements of the Underwriters Laboratories, the National Electrical Manufacturers Association, and the Institute of Electrical and Electronics Engineers. In addition, standards for seismic safety fire protection, and staff safety cut across other industry codes or standards. When identifying critical characteristics, decision makers must consider each of these factors.

Once critical characteristics are identified, a criterion for acceptance of a specific order at a specific site must be identified. The NCIG-07 guideline cites four methods. Method 1 conducts special receipt inspections and tests or postinstallation tests of the critical characteristics. Method 2 relies on the supplier's commercial quality controls, under certain conditions, which are verified and documented through surveys. Method 3 provides for source verification of a single item, or lot of items, before the supplier ships it. Method 4 establishes a documented supplier/item performance record.

Building the CGI Database

Technical evaluations are complete or nearing completion for 56 items (see the accompanying list). When an evaluation has been approved by the JUTG, the item is entered in the CGI Database in EPRINET. Database users can access six types of information screens for each item:

- The first, Basis for Technical Evaluation, summarizes intended functions, the safety function, critical design characteristics, and criteria for acceptance.
- The second, Item Identification, provides information about environmental and seismic qualification
- The third, Critical Characteristics of Design, shows which properties (materials, dimensions, mechanical and electrical attributes) are essential for an item's unique form, fit, and function.
- The fourth, Selection of Critical Characteristics and Acceptance Criteria, lists functions, values or requirements for each function, and acceptance ranges for measurable attributes.
- The fifth, Selection of Acceptance Method, lists applicable NCIG-07 acceptance methods and sampling criteria for determining whether critical characteristics are maintained in a given lot of the item. This screen set also recommends supplier surveys, source verification, and performance records where appropriate for use in dedicating the item.
- The sixth screen set describes inspection and testing methods, references, and attachments.

The CGI Database is easily accessible to any EPRI member through EPRINET. A popular, reliable, and efficient database structure with a custom-designed front end supports natural language searches as well as precision keyword searches. EPRINET is available to Macintosh and IBM PC compatibles through Tymnet, a popular communication network, as well as through IBM IIN, Host to Host, and direct dial-in via modem.

For more information about the CGI effort, contact EPRI's Warren Bilanin at (415) 855-2784 or (704) 547-6123.

Residential Program

Measuring and Modeling Residential Infiltration

by John Kesselring, Customer Systems Division

Air infiltration into residential buildings has a major effect on both heat loss and indoor air quality. In recent years, the weatherization of homes to reduce energy consumption has helped produce well-insulated, energy-efficient buildings in which airflow and heat loss are reduced. Past assumptions that natural infiltration provides adequate ventilation for a home may no longer be valid for today's tight, well-insulated homes.

Several recent research projects sponsored by the Bonneville Power Administration (BPA) have measured the heating-season infiltration characteristics of more than 425 all-electric homes. Infiltration was measured by means of the passive, time-averaged perfluorocarbon tracer system developed at Brookhaven National Laboratory. Natural infiltration also was estimated by using data from house pressurization tests in conjunction with an infiltration model developed at Lawrence Berkeley Laboratory (LBL). On average, the homes were fairly tight and had low ventilation rates: 50% of typical new homes and 73% of energy-efficient homes would fall below the new minimum ventilation standards prescribed by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). Overall, the studies suggest that recently constructed homes may need mechanical ventilation to meet ASHRAE standards.

The RVC and infiltration studies

Although the successful development of practical and efficient residential ventilation technologies is rapidly becoming imperative, the technical resources needed to perform R&D on residential ventilation cannot be supplied by any individual organization. Recognizing this, several organizations interested in the advancement of energy-efficient, pollution-

ABSTRACT *In recent years, as tighter building envelopes were constructed and building infiltration rates were reduced to save energy, mechanical ventilation systems became a crucial tool for increasing airflow and improving indoor air quality. To improve understanding of natural infiltration and of interactions between mechanical ventilation systems and natural infiltration, EPRI sponsored a study in which residential infiltration data, gathered with new techniques, were used to help refine existing infiltration models. Improved models should prove instrumental in the design of future mechanical ventilation and air-cleaning systems.*

controlling ventilation technologies formed the Residential Ventilation Consortium (RVC). By pooling funds for R&D activities, RVC members intend to sponsor an integrated research program to study infiltration, promote the implementation of effective residential ventilation technologies, and maximize associated improvements in indoor environmental quality. Current members include EPRI, which serves as the consortium coordinator; BPA; Honeywell, Inc.; and Pacific Gas and Electric Company.

The LBL infiltration model is the most widely used method of predicting infiltration and ventilation rates in residential buildings. The model has remained substantially unchanged since it was completed in 1980 and incorporated into the 1981 ASHRAE Handbook of Fundamentals. Since then, however, research has shown that in certain regimes the LBL model overestimates infiltration. In RP2034-40 (with support from the RVC), Ecotope, Inc., and LBL are trying to improve the model by correlating predictions with field measurements from a carefully selected sample of houses, and by examining how leakage distribution and other factors influence infiltration. The RVC expects a revised model to improve predictions of natural infiltration and assessments of ventilation needs, thereby proving instrumental in the design of future mechanical ventilation and air-cleaning systems.

New technique for measuring infiltration

Ecotope studied four homes that were equipped with either mechanical ventilation systems or forced air distribution systems or both, and that were exposed, to various degrees, to the wind. Measurement protocols were designed to quantify the infiltration impacts of ventilation systems, air handlers, and natural driving forces. Natural infiltration stems from two driving forces: wind-generated pressures on the building exterior (the wind effect) and buoyancy pressures, which result from indoor-outdoor temperature differences (the stack effect). In each home, pressure differences were measured across the floor and the ceiling, as well as across the exterior faces. Pressure data were recorded every 30 to 60 seconds, depending on the site. Anemometers with relatively low cut-in speeds measured wind speed and direction at each site.

The living areas of each home were divided into two tracer zones, with each floor in a two-story home constituting a tracer zone. Attics, crawl spaces, and garages also were treated as separate zones in order to improve understanding of the flows through each of these areas and the leakage distribution of the house.

Infiltration and interzonal flows were measured by using LBL's multitracer measurement system (MTMS), which injected constant quantities of tracer gases into the various zones and measured the concentration of each gas in each zone. LBL technicians included several injection and sampling points in each zone; they also equipped each zone with a continuously operating mixing fan and with temperature sensors. The MTMS made one complete cycle through the zones every 1.5 to 4 minutes, and temperatures were measured once per cycle. Using the MTMS injection and concentration measurements, a computer program calculated flows between each zone and the outside, as well as flows between zones. To assess the envelope leakage, the technicians used blower doors to perform pressurization tests at each site and measured flows through exhaust and central air-handler fans.

Real-time multizone flow measurement, combined with concurrent pressure and temperature measurement, constitutes a powerful new tool for understanding airflows in homes. The homes included in the study were relatively tight in terms of specific leakage area, air changes per hour (ACH) at 50 Pa (0.2 in. of water), and natural infiltration. Stack-effect infiltration (as predicted by the LBL model) was dominant in these homes, constituting 84–97% of natural infiltration and 58–70% of total infiltration. Ventilated attics and crawl spaces had high infiltration rates: the attic rates ranged from 3.1 to 6.0 ACH, and the crawl space rates, from 2.4 to 7.2 ACH. Infiltration in these areas was due almost entirely to wind; the rates, like the lower infiltration rates for the garage, bore a strong correlation with wind speed.

Modeling infiltration

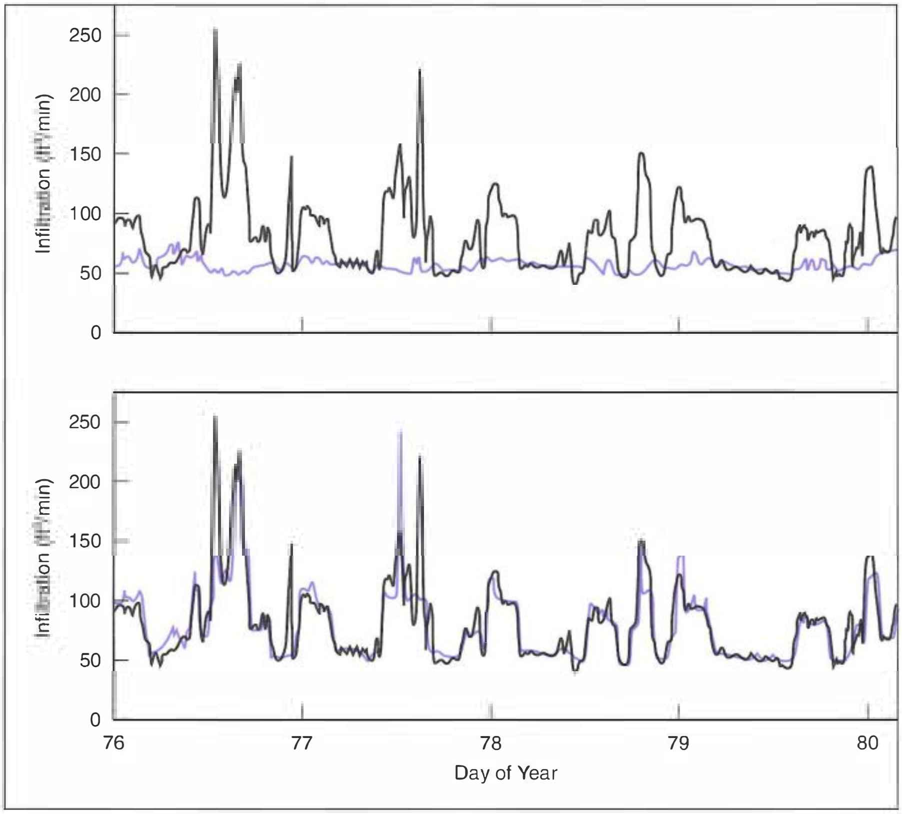
Ecotope used two infiltration models in RP2034-40, the LBL model and the Alberta Infiltration Model (AIM2). Developed at the University of Alberta, AIM2 can be viewed as a simple extension of the LBL model, although it incorporates several refinements. Both models combine weather data and pressurization data from blower-door tests to predict infiltration due to stack and wind effects. To improve the LBL model, which bases the stack effect on the full height of a home, Ecotope calculated average stack heights. This simple compensation method, validated in previous projects, reduced stack effects predicted with the LBL model by about 10%.

Each model's predictions were compared with actual infiltration measurements for periods when only natural infiltration was occurring. Although the two models have many similarities, they produced systematically different results. For all sites, the LBL model predicted combined wind and stack infiltration effects 30–60% greater than AIM2 predicted. While the magnitude of difference may be somewhat alarming, the model predictions did bound the measurements. Detailed comparisons of predicted and measured infiltration do not indicate that either model is clearly superior. The differences in predictions stem primarily from the way the models use measurements of building tightness.

The standard method for characterizing tightness is to pressurize or depressurize the building by using a blower door and then to make flow measurements over a range of pressures from 15 to 70 Pa. The data generally appear to follow a power curve—called the leakage function of the building—with flow proportional to some power of pressure difference. Typically, the data from many thousands of field blower-door tests fit power curves quite well. Because of technical difficulties, however, such as interference from stack and wind effects, these tests are rarely done at pressures below 15 Pa, although the actual pressures across building envelopes are much lower. As measurements at the test homes indicate, naturally induced pressures are about 1–2 Pa (or less, if a home is somewhat sheltered from the wind). Thus, leakage functions determined by tests at high pressure are being extrapolated far beyond the measurements on which the functions are based.

The LBL model uses the leakage function to predict the flow at 4 Pa and then uses a square-root law, while the AIM2 model uses the power curve from the pressurization test. The determination of which method, if either, should be used to extrapolate blower-door test data to lower pressures depends on the specific nature of the leaks in each home and cannot be predicted by theory. The key issue is the nature of the leakage function in real buildings at low pressures (0–4 Pa), and it now appears that field measurements under windless conditions are needed to resolve this issue.

Figure 1 Field data (black) and model predictions (color) for one house in the Ecotope residential infiltration study. In the top graph, predictions of natural infiltration (both stack and wind effects) made by the LBL model are compared with data on total infiltration. Agreement is good, considering that the data spikes are the result of mechanical ventilation systems. To account for these effects, Ecotope developed a simplified fan model. Predictions in the bottom graph incorporate output from that model and show impressive agreement with the data.

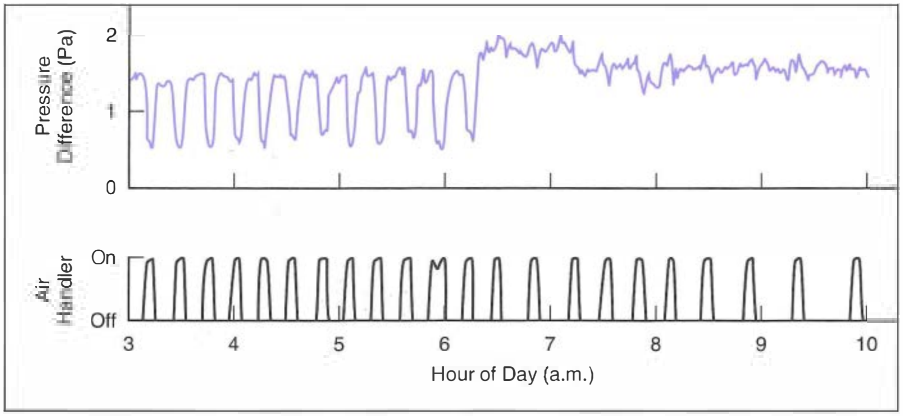


Fans, air handlers, and duct leakage

Mechanical systems can significantly affect infiltration rates. Using actual living-zone infiltration data, Ecotope estimated the added infiltration caused by exhaust fans and air handlers (with associated duct leakage). Ecotope then developed and validated a simplified fan model that can be used with any natural infiltration model to predict both the infiltration due to operation of exhaust or supply fans and the total infiltration (Figure 1). One implication of the model and the measured data is that unbalanced fan flows interact strongly with natural infiltration. Even in the fairly tight test homes, fans typically delivered only half their rated capacity.

Air handlers and associated ductwork systems, which interact with natural infiltration in a more complex way than fans, can also have a large effect on living-zone infiltration rates. Surveys have shown that overall infiltration rates are about 15–36% greater in homes with air handlers than in comparable homes with-

Figure 2 Effect of air handler operation and door closing on house pressures at an Ecotope study site. Shown are the air handler signal and the pressure difference across the envelope at the ceiling. At night, when the bedroom door is closed, the operation of the air handler depressurizes the house relative to the outside ambient pressure. (That is, the buildup of air in the bedroom, which has no return duct, leads to depressurization of the rest of the house.) As a result, more outside air infiltrates into the house, and heating costs rise. The occupants open the bedroom door at 6:30 a.m., stabilizing the pressure in the house.



out such systems. Three distinct effects are involved: (1) duct leakage when the air handler is running, (2) increased natural infiltration due to duct leaks and envelope penetration leaks, and (3) induced infiltration due to the closing of interior doors. The fan model deals only with the effects of duct leakage.

At the three homes with central air handlers, pressurization tests were used in conjunction with the fan model to estimate the added infiltration and the fraction of leakage traceable to the duct system. One significant finding was that closing even a single bedroom door when the air handler is running creates a sufficiently large pressure differential between the bedroom and the part of the home where the return is located to cause a major increase in infiltration (Figure 2).

Further research

The most significant issue raised in Ecotope's study concerns the nature of the leakage function at low pressures. With RVC support, Ecotope is now developing a special test device—a mini–blower door—designed to make accurate leakage function measurements at low pressures (0–4 Pa).

Researchers will conduct low-pressure tests at the four homes and then perform reanalyses of the earlier data. They will also collect a full set of data at a gas-heated home and at two electrically heated homes, one of which is located on a windy site. By taking measurements at a home with greater wind exposure, in which wind and stack effects alternately dominate, researchers hope to gain insights about the combination of those effects and about the appropriate wind pressure coefficients for floor and ceiling. This knowledge can then be used to improve infiltration modeling.

Transmission

Advances in Metal Oxide Varistor Technology

by Harshad Mehta, Electrical Systems Division

Improving certain characteristics of zinc oxide (ZnO) disks used in surge arresters can yield a variety of benefits. For example, increasing the energy-absorbing capability of a given varistor can make it possible to reduce the number of parallel columns in an arrester unit used in series capacitor protection or other applications requiring high energy dissipation. Alternatively, an increase in energy-absorbing capability can make it possible to eliminate the parallel trigger gap and associated controls used to bypass the varistor during extreme system faults. In standard station arrester applications, a unit with such superior energy-handling capability could lead to new designs that require less ZnO material.

To realize these benefits, EPRI has recently sponsored three projects on ZnO varistor technology. One effort (RP2667-1), conducted by Westinghouse, focused on increasing the energy-absorbing capability of today's varistors by as much as a factor of 10. The knowledge gained in this project, which demonstrated a fivefold increase in this capability, has been incorporated into an expert system that can predict varistor properties and hence support the design of varistor materials (RP2667-4). EPRI has also pursued the improvement of varistor performance through more-fundamental research with General Electric that examined a variety of varistor characteristics (RP2667-2).

Energy-absorbing capability

The primary function of ZnO surge arresters is to discharge lightning surges and limit the voltage in order to prevent damage to electrical equipment. Surge arresters are also used to limit switching-surge voltages, which vary in peak value and duration depending on the application. In addition, arresters must be capable of withstanding momentary 50- or 60-

Hz overvoltages lasting for several power frequency cycles.

Since a varistor absorbs energy by converting electric energy to heat through joule heating, its temperature increases in direct relation to the transient energy absorbed. For a variety of temporary overvoltage situations, the varistor must absorb large amounts of energy without failure due to thermal runaway, puncture, or cracking.

Applications that require high energy absorption in surge arresters include series capacitor protection and dynamic overvoltage suppression. For these applications, the energy absorption capability of the arresters can be improved by increasing the number of small ZnO elements stacked in parallel, by enlarging the diameter of the elements, or by increasing the energy absorption capability of the ZnO varistor itself.

The paralleling of varistor elements, the first option, necessitates precise control of the nonlinear voltage characteristics of each element—a costly procedure—and requires more materials and a larger housing. In the second option, enlarging the elements, electrical nonuniformities caused by density variations, ZnO grain-size distribution, and other factors that lead to nonhomogeneous structure become critical. Because of the difficulties presented by these alternatives, EPRI has focused on the third option—increasing the energy absorption of the varistor itself. This is also the lowest-cost approach.

In RP2667-1, Westinghouse investigated ways to improve energy absorption by modifying conventional varistor additives and by adding new materials. Westinghouse personnel at both the Science and Technology Center in Pittsburgh and the Transmission and Distribution Components Division in Bloomington, Indiana, participated in this effort.

The researchers conducted an extensive study of sintering conditions and postsintering treatments. They measured electrical properties on each of five disk samples per condition, performed a 250°C test of the leakage current stability as an indication of the potential for high-energy-arrester application, and conducted a destructive 60-Hz energy absorption test. Microstructural characterization,

ABSTRACT *Arresters play a vital role in protecting substation equipment from high-voltage surges caused by switching, lightning, and other phenomena. Metal oxide varistors, especially zinc oxide disks, are key components of any modern arrester unit. EPRI has developed new zinc oxide disks with increased energy-absorbing capability that promise to lead to smaller, lighter, and more economical arrester installations for a variety of applications.*

artificial intelligence techniques, and electrical property modeling were used. In addition, several high-energy-absorbing compositions were piloted, and many scale-up batches were evaluated for reproducibility of properties, manufacturability, and process yields in a normal manufacturing plant environment.

Out of 71 new compositions and several hundred processing modifications evaluated, five formulations were developed with a production-batch-average energy absorption of about 900 J/cm^3 and electrical properties suitable for arrester application (Figure 1). Moreover, the energy absorption results achieved at the R&D level were significantly higher than the production-batch averages.

Since the energy absorption capability of conventional varistors ranges from 150 to 200 J/cm^3, these improvements can potentially reduce by a factor of 4 to 5 the number of parallel columns in an arrester unit for high-energy-absorption applications, such as series capacitor protection. The new procedures involve only minor modifications to conventional varistor fabrication practices (see EPRI report EL-7155). However, because Westinghouse-Bloomington's product line is now owned by Asea Brown Boveri, which uses a different production technology, the direct application of the developments is probably not possible.

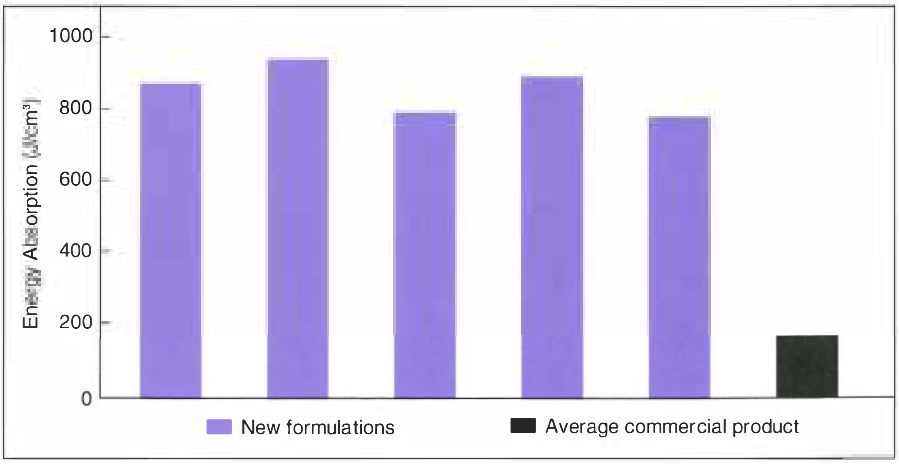


Figure 1 Five different new formulations of zinc oxide varistor disks have production-batch-average energy-absorbing capabilities significantly higher than the capabilities of commercially available varistors. The use of such improved materials could lead to lower equipment costs for arresters in high-energy-absorption applications.

Expert system

The work under RP2667-1 produced a large database of experimental results. To preserve and build on the knowledge gained in this work, Westinghouse has developed an expert system under EPRI contract. Called VARISTOR, the system combines the knowledge in the RP2667-1 database with data from other sources, and it captures the result in a user-friendly computerized format.

On the basis of varistor composition and processing variables specified by the user, the expert system can predict varistor properties. It provides the details in a report, which includes a description of the logic used to reach the conclusion. The expert system is a valuable aid to the design of new varistor materials and could lead to improved performance, higher reliability, and lower cost for arrester-related utility applications. An EPRI report on VARISTOR will be published this fall.

Fundamental varistor research

While work under RP2667-1 focused on the goal of increasing varistor energy absorption capability, the related project with General Electric (RP2667-2) has taken a broader view, simultaneously examining several varistor characteristics. This project was necessary because varistor characteristics are interdependent; that is, improvements in one area may affect other characteristics and possibly lead to degraded performance. Hence the GE researchers sought to determine what combination of improvements in varistor characteristics could optimize performance.

One key parameter examined was the nonlinear exponent α in the equation $I = kV^{\alpha}$, where I is current, k is a constant, and V is voltage. The equation is applicable in the nonlinear region of a varistor's current-voltage characteristic. If the volume of a standard surge arrester disk is decreased to take advantage of increased energy-handling capability, the current density on switching surges increases. Because of the current-voltage characteristic of a varistor, α decreases as the current rises. At a high current, such as 10 kA, reducing the cross-sectional area of the disk increases the voltage. Thus arresters fabricated from such disks would exhibit degraded protection characteristics at high currents. Specifically, a reduction in the standard diameter of one disk from 76 to 60 mm would increase the voltage at 10 kA by 5% and would require an improvement in α of about 10%. For standard station arrester applications, the GE researchers developed a formulation that would in fact increase α by 10%.

Another parameter examined in this project was the watts loss (heat) dissipation of the arrester. Once the energy-handling capability of a varistor has been enhanced, the device must be able to dissipate the watts losses generated as a result of the increase in temperature due to an energy pulse. For example, 500 J/cm^3 applied to a 76-mm by 35-mm disk used for series capacitor protection will raise the temperature 160°C. With an ambient temperature of 40°C, the resulting disk temperature would be 200°C. At this temperature, the watts losses in the disks would have to be reduced by 70% to prevent thermal runaway. In fact, the researchers were able to reduce the losses by 75%. While attaining such reductions for standard station arresters is more difficult, significant progress was made toward this end (see EL-6960).

The EPRI projects have advanced the state of the art in metal oxide varistor technology. Eventually the result will be improved performance at lower cost in utility transmission substations and overhead transmission applications. Future work may result in the application of these basic improvements in technology to distribution system equipment as well.

Land and Water Quality

MOSES: Mineral Oil Spill Evaluation System

by Ishwar P. Murarka, Environment Division

New regulations to be proposed under the federal Clean Water Act and the Resource Conservation and Recovery Act may require utilities to prepare and implement plans for spill prevention, control, and countermeasures for all aboveground tanks containing oils, including utility substation equipment and storage tanks. The regulations may also require the installation of structures around equipment to completely contain a spill of the maximum size that can occur over a 72-hour period. Given such a requirement, utilities will need a method for deciding whether to build additional containment structures.

In response, EPRI sponsored the development of a personal-computer-based code, the Mineral Oil Spill Evaluation System. The MOSES code can be used to estimate the probability that spills from substation equipment or surface storage tanks will reach surface water. On the basis of the computed probability, utilities can decide what is necessary to ensure compliance with spill prevention, control, and countermeasure regulations.

MOSES models a variety of processes, accounting for infiltration, on-site storage, volatilization, the effects of soil and vegetation cover on flow, off-site retention, transport by overland flow, and the effects of rainfall (Figure 1). It has a Monte Carlo routine for selecting input values from user-defined ranges for spill volumes and several site characteristics.

Using MOSES

MOSES runs on microcomputers that are true IBM compatibles and that have at least 640

ABSTRACT *EPRI has developed the MOSES code to help utility staff and others predict the likelihood that spills of mineral oil from substation equipment and aboveground storage tanks will reach surface water. The code is particularly useful for utility managers and engineers responsible for developing spill prevention plans and implementing spill control measures. MOSES computes the probabilities of spills remaining on-site and of spills reaching surface water for a wide range of environmental and site conditions. Designed for use on IBM-compatible personal computers, the code is commercially available through the Electric Power Software Center.*

kilobytes of memory, a math coprocessor, and an EGA or VGA color graphics card and a color monitor (although a monochrome monitor can be used). The code can be run from a high-density floppy drive, but the use of a hard disk is highly recommended. Plots can be printed by a wide variety of laser and dot-matrix printers.

MOSES can be used to estimate the probability that spills—ranging from a small leak in a circuit breaker or a transformer to the failure of a large tank—will remain on-site or will reach nearby surface water. Information on the likelihood of spills reaching water bodies can be used to help determine whether more on-site storage is needed. In addition, the code can be used to estimate the effects of changes in substation design (e.g., the area and depth of gravel beds or on-site trenches and diversion channels) on the probability of spills reaching water bodies.

As input to the MOSES code, the user must supply site-specific data on the characteristics of the substation or tank area, the distance to the nearest surface water, the characteristics of the area between the equipment site and the surface water, and the off-site storage capacity. The user must also specify the characteristics of the oil being simulated (default values for mineral oil are provided), the spill volume distribution, and the probability that a spill could occur. The data are entered via a series of on-screen menus. Once entered, the data can be saved for later retrieval.

The code computes the following:

- The probability that a spill will remain on-site, given that a spill occurs
- The combined probability that a spill will occur and that it will remain on-site
- The probability that a spill will occur and will reach surface water

The probability that spills will reach surface water can be determined either for dry conditions only or—by taking into account rainfall data supplied by the user—for both wet and dry conditions. In general, the probability that spills will reach surface water increases under wet conditions, since rainwater can fill all or part of the available storage and can transport droplets of oil by overland flow.

The results from MOSES are presented as graphs showing relative frequency distributions for the spill volumes contained on-site, the spill volumes actually reaching nearby surface water, and the time required to reach the water. For cases where spills reach surface water, MOSES generates relative frequency distributions showing the distances to surface

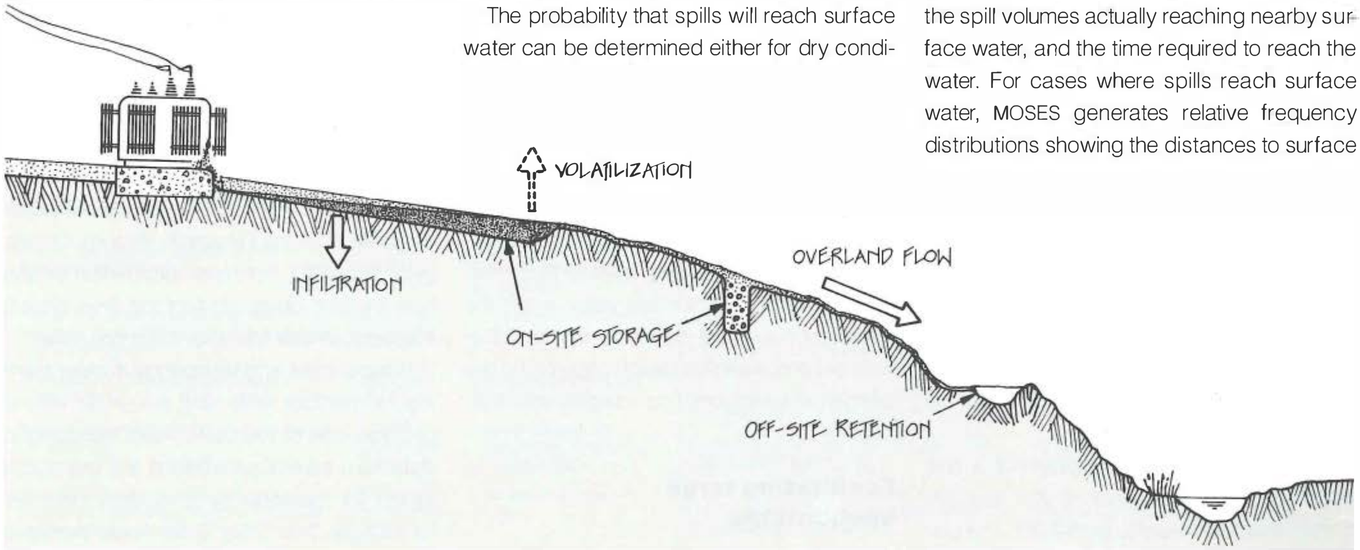


Figure 1 To predict the fate of mineral oil spills from substation equipment and aboveground storage tanks, the MOSES code simulates various storage and transport processes. MOSES takes into account both on-site and off-site factors, as well as the effects of rainfall on storage capacity and oil transport.

Table 1
SAMPLE INPUT DATA SET

On-site Substation Description	Lower Limit	Upper Limit
Spill storage capabilities		
Area of gravel bed (m^2)	40	160
Depth of gravel depression (m)	0.15	0.23
Gravel porosity	0.4	0.6
Infiltration rate of water through bottom of gravel bed (cm/h)	0.3	0.5
Volumetric capacity of other on-site control structures (m^3)	0.2	2.2
Probability that spill will occur (per year)		0.0026

Off-site Substation Description	Lower Limit	Upper Limit
Distance to nearest surface water (m)	10	400
Estimated width of potential channel where mineral oil will flow (m)	0.3	3.0
Estimated detention storage depth (cm)	0.1	2.0
Volumetric capacity of off-site spill control structures in flow direction (m^3)	0.1	1.0
Infiltration rate of water through soil surface (cm/h)	0.1	5.0
Wind speed (m/s)	0	10
Land slope (m/m)	0	0.05
Manning's n	0.03	0.08

Spill Scenario Description	Distribution Used	Lower Limit	Upper Limit	Mean
Volume of spill (m^3)				
From transformer	Exponential	0.07	12.0	4.5
From circuit breaker	Exponential	0.01	1.5	1.3
Duration of spill (h)		0.01	48.0	

Note: The case used the default values for mineral oil (at 20°C): average molecular weight, 200; viscosity, 5 cp; specific gravity, 0.822 g/cm³

water and the spill sizes. Plots can be viewed on-screen, printed out, or sent to a file for later use in a word processing or other software package.

Sample case

To illustrate how MOSES can be used to estimate the fate of spilled oil, a case involving a substation with one transformer and two circuit breakers was run. Table 1 presents the sample input data set. The probability of a spill from the transformer or a circuit breaker occurring was assumed to be 0.0026 per year. The substation had a gravel bed providing on-site spill storage capacity. The case assumed that no rain was falling at the time of a spill. The calculations presented below are the result of 100,000 simulations.

In this example the probability that a spill would remain on-site, given that a spill occurred, was calculated to be 0.9472. The calculated joint probability of spills occurring and being contained on-site was 0.99986. The calculated joint probability of spills occurring and reaching surface water was 0.00000777.

MOSES was also used to calculate the probabilities for a variation of this case: all the conditions were the same except that the volume of the substation gravel pack was doubled. With the additional gravel, the probability that a spill would remain on-site, given that a spill occurred, increased from 0.9472 to 0.99649. Further analysis indicated that doubling the volume of gravel would reduce the likelihood of smaller spills reaching surface water; MOSES predicted that only spills of 10.5 m^3 or larger would reach surface water when the volume of the gravel pack was doubled. Results like these can be used in optimizing the design of structures and containment systems.

Facilitating large applications

A multirun driver has recently been developed for MOSES to speed up applications involving large substations. The driver, still in the testing stage, lets the user make runs using different data sets for individual pieces of equipment. This feature allows for the fact that certain characteristics, such as distance to surface water and land slope, can vary at large sites. Also, the user can select uniform probability distributions for small leaks from pieces of equipment like circuit breakers and exponential distributions for larger pieces like transformers. (Uniform distributions assume that spills of various sizes are equally probable; exponential distributions assume that larger spills have a lower probability of occurring than smaller spills.) The code runs each data set sequentially and stores the results. The output shows the probabilities of spills remaining on-site and of spills reaching surface water for each piece of equipment.

The new driver also lets the user determine how much additional on-site storage would be needed to keep spills from a particular piece of equipment from migrating off-site. The user selects a unit (e.g., a transformer) and an incremental increase in on-site storage (e.g., 10%). MOSES then makes successive runs, adding that increment of storage each time, and checks the probability of a spill remaining on-site. If that probability is less than 1, MOSES makes another run, increasing the on-site storage another 10%. If the spill would remain on-site, the code stops and prints out the number of runs made, the final on-site storage used, and the resulting final probabilities.

Technology transfer

MOSES is commercially available through the Electric Power Software Center, (214) 655-8883. A user's manual, EPRI report EN-7188, is available from the Research Reports Center, (415) 965-4081. For more information on the new multirun driver, contact the EPRI project manager, Ishwar Murarka, (415) 855-2150.

Case studies and technology transfer training for member utility staff are under way to promote use of the code. Also, site-specific data from several substations are being collected for inclusion as a resident data set for MOSES. The Utility Solid Waste Activities Group is cofunding the data collection aspects of this research.

New Contracts

Project	Funding/ Duration	Contractor/EPRI Project Manager
Customer Systems		
Electric G-Van Demonstration and Commercial Development (RP1569-13)	$2.134,200 66 months	Conceptor Industries/ *J. Janasik*
Residential Technical Assessment Guide (TAG) Update (RP2034-43)	$89.300 11 months	EnTechnology/ *J. Kesselring*
Economic Analysis of Advanced Heat Pump Systems (RP2417-17)	$185,000 24 months	National Institute of Standards and Technology/ *J. Kesselring*
Electric Vehicle Range Extension Options (RP2882-14)	$61,500 8 months	W. I. Whiddon & Associates/ *G. Purcell*
Microwave Clothes Dryers (RP3188-7)	$98,000 12 months	Thermo Energy Corp./ *J. Kesselring*
Metals, Glass, and Minerals Production (RP3243-1)	$1,247,300 11 months	Carnegie-Mellon University/ *P. McDonough*
Electrical Systems		
System-Reliability-Based Design of Transmission Lines (RP1352-11)	$98,500 13 months	University of Maine/ *P. Lyons*
Mutual Design of Power Lines and Railroad Facilities (RP1902-7)	$224,000 22 months	Northwestern University/ *J. Hall*
Adaptive Out-of-Step Protection: Algorithm Analysis and Development (RP3022-8)	$60.000 24 months	Virginia Polytechnic Institute and State University/ *L. Mankoff*
Fuse Operation Sensors (RP3080-2)	$59,100 6 months	ABB Power T&D Co./ *J. Porter*
Power System Dynamic Security Analysis Using Time Domain Techniques: Feasibility Evaluation (RP3103-1)	$351,300 21 months	Arizona State University/ *G. Cauley*
Knowledge-Based Systems for Improved Adaptive Relaying and Diagnostics on Distribution Feeders (RP3127-1)	$51,300 14 months	Texas A&M Research Foundation/ *T. Kendrew*
Control and Design for Service Restoration Under Emergency Conditions (RP3127-2)	$50,000 14 months	North Carolina State University/ *T. Kendrew*
Long-Term Dynamic Requirements Study: User Needs, Existing Models, and Data Availability (RP3144-2)	$235,700 15 months	Ontario Hydro/ *M. Lauby*
Underground Transmission Magnetic Field Management (RP7898-37)	$52,700 11 months	Power Technologies/ *J. Shimshock*
Large Locked Castings Using Expanding Monomer Polysil (RP7919-1)	$101,400 15 months	Westinghouse Electric Corp./ *B. Bernstein*
Environment		
Animal Toxicological Studies of Acid Aerosols (RP2155-2)	$779,600 32 months	New York University Medical Center/ *L. Goldstein*
Animal Toxicological Studies of Acid Aerosols: Molecular Approaches in Guinea Pigs (RP2155-3)	$337,100 36 months	University of Cincinnati/ *L. Goldstein*
Atmospheric Sciences Data Center (RP2262-3)	$134,200 34 months	Sigma Research Corp./ *M. Allan*
Climate Systems Modeling: State of the Art (RP2333-12)	$186.400 24 months	University Corp. for Atmospheric Research/ *C. Hakkarinen*
Theoretical Study: Relative Importance of Natural and Man-Made Factors in Climate Change (RP2333-14)	$176,100 36 months	Dartmouth College/ *A. Quinn*
SARMAP Modeling (RP3189-5)	$730,000 36 months	San Joaquin Valley Joint Powers Agency/ *A. Hansen*
Risk Factors for Sporadically Occurring Legionnaires' Disease (RP3266-1)	$474,700 15 months	Ohio State University/ *J. Yager*
Exploratory and Applied Research		
Strain Selection and Optimization for Coal Bioprocessing (RP8003-25)	$520.000 23 months	Genecor International/ *S. Yunker*
Optical pH Sensors for High-Temperature Environments (RP8004-6)	$398,700 35 months	Research International/ *T. Passell*
Monitoring of Check Valves by Means of Neural Networks (RP8010-12)	$112,700 11 months	University of Tennessee/ *J. Naser*
Development of Neural Network Controller for Power Systems (RP8010-13)	$456,400 35 months	Stanford University/ *J. Maulbetsch*
Automated Recognition of Hand-Lettered Text (RP8010-16)	$854,000 35 months	Kaman Sciences Corp./ *J. Naser*
Sequential Optimization: Formulation Methodology and Results Interpretation (RP8010-17)	$200.000 12 months	Decision Focus/ *S. Yunker*
Cold Fusion Studies (RP8012-2)	$500,000 29 months	Texas A&M University/ *D. Worledge*
Fast-Pulse Arcs in Air (RP8012-8)	$75,000 12 months	University of Nebraska, Lincoln/ *M. Rabinowitz*
Generation and Storage		
Strategic Storage Benefits: Compressed-Air Energy Storage Versus Combustion Turbines (RP1084-47)	$97,900 11 months	Decision Focus/ *R. Schainker*
Technical and Economic Assessment of Molten Carbonate Fuel Cell Manufacturing Concepts (RP1677-22)	$182,000 7 months	Michael A. Cobb and Co./ *E. Gillis*
Development of the ESPert Computer Program (RP1835-24)	$229,500 12 months	P. Gelfand Associates/ *R. Altman*
Ultrasonic Measurement of Film Thickness and Temperature in Hydrodynamic Bearings (RP1864-7)	$60,000 24 months	TecSonics/ *M. Blanco*
Utility Continuous Emission Monitoring Database (RP1961-8)	$180,800 29 months	Engineering Science/ *R. Binsol*
Materials Testing at the PRENFLO Coal Gasification Plant (RP2048-11)	$118,100 26 months	Gesellschaft für Kohle-Technologie/ *W. Bakker*
Compressed-Air Energy Storage Compact Simulator (RP2488-18)	$88,300 6 months	Science Applications International Corp./ *R. Pollak*
Nuclear Power		
Demonstration of Performance Characteristics of SVEA-96 Fuel in U.S. Reactors (RP1580-19)	$200,000 42 months	ABB Atom/ *O. Ozer*
Dose Rate at B&W Reactor Plants (RP2494-4)	$59,600 6 months	Babcock & Wilcox Co./ *H. Ocken*
Plant Information Network Implementation Pilot Project (RP2514-11)	$70,400 7 months	Pacific Gas and Electric Co./ *W. Bilanin*
Maintenance Application Guide for GE Low-Voltage Circuit Breakers (RP2814-40)	$105.100 7 months	Grove Engineering/ *J. Christie*
Evaluation of Installed Low-Voltage Cables: Test Planning (RP2927-9)	$50,000 5 months	ERC Environmental and Energy Services Co./ *G. Sliter*
Development of Steam Generator Vessel Database (RP3147-2)	$99,800 8 months	Science Applications International Corp./ *S. Liu*
Influence of Roughness on Mass Transfer (RP3170-16)	$56,400 12 months	NEI International R&D Co./ *B. Chexal*

New Technical Reports

Requests for copies of reports should be directed to Research Reports Center, P.O. Box 50490, Palo Alto, California 94303; (415) 965-4081. There is no charge for reports requested by EPRI member utilities. U.S. universities, or government agencies. Reports will be provided to nonmember U.S. utilities only upon purchase of a license, the price for which will be equal to the price of EPRI membership. Others pay the listed price. Research Reports Center will send a catalog of EPRI reports on request. To order one-page summaries of reports, call the EPRI Hotline, (415) 855-2411.

CUSTOMER SYSTEMS

Adjustable-Speed Drive Applications: City of Chicago Water Pumping System Analysis
CU-7223 Final Report (RP2951-4); $200
Contractor: CRS Sirrine Engineers, Inc.
EPRI Project Manager: M. Samotyj

ENVIRONMENT

Selenium Biogeochemistry in Reservoirs, Vol. 1
EN-7281 Final Report (RP2020-1); $200
Contractor: Old Dominion University
EPRI Project Manager: D. Porcella

Use of Batch and Column Methodologies to Assess Utility Waste Leaching and Subsurface Chemical Attenuation
EN-7313 Interim Report (RP2485-8); $200
Contractor: Battelle, Pacific Northwest Laboratories
EPRI Project Manager: I. Murarka

GENERATION AND STORAGE

Analyses of Two-Stage Coal Liquefaction Processes
GS-7074 Final Report (RP832-11); $200
Contractor: Lummus Crest Inc.
EPRI Project Manager: W. Weber

Coal Quality Information Book (Second Edition), Vols. 1 and 2
GS-7194 Final Report (RP1400-23); $250 each volume
Contractor: CQ Inc.
EPRI Project Manager: D. O'Connor

Development of Internal Reforming Molten Carbonate Fuel Cells
GS-7221 Final Report (RP2344-1); $200
Contractor: Energy Research Corp.
EPRI Project Manager R. Goldstein

Technical Feasibility and Cost of Selective Catalytic Reduction NO_X Control
GS-7266 Final Report (RP1256-7); $500
Contractor: United Engineers and Constructors, Inc.
EPRI Project Manager: E. Cichanowicz

Amorphous Silicon Alloys for Tandem Solar Cells
GS-7285 Interim Report (RP2824-2); $200
Contractor: Princeton University
EPRI Project Manager: T. Peterson

Photovoltaic System Performance Assessment for 1989
GS-7286 Interim Report (RP1607-6); $200
Contractor: Southwest Technology Development Institute
EPRI Project Manager: J. Schaefer

Lithium Manganite Development as a Molten Carbonate Fuel Cell Cathode
GS-7288 Final Report (RP1085-15); $200
Contractor: Argonne National Laboratory
EPRI Project Manager R. Goldstein

Proceedings: Feedwater Heater Technology Conference
GS-7290 Proceedings (RP1887-4); $200
EPRI Project Manager: J. Tsou

Two-Stage Coal Liquefaction Integration Configurations: Advanced Coal Liquefaction R&D Facility, Wilsonville, Alabama
GS-7293 Interim Report (RP1234-1, -2); $200
Contractor: Southern Company Services, Inc.
EPRI Project Manager: W. Weber

Guidelines for the Use of Refractories in Circulating-Fluidized-Bed Combustors
GS-7304 Final Report (RP979-27); $200
Contractor: M. S. Crowley
EPRI Project Manager: W. Bakker

Operation and Maintenance Experiences of Pumped-Storage Plants
GS-7325 Final Report (RP1745-15); $200
Contractor: Morrison-Knudsen Engineers, Inc.
EPRI Project Manager: C. Sullivan

INTEGRATED ENERGY SYSTEMS

Central Appalachia: Coal Industry Profile
IE-7115 Final Report (RP3199-2); $200
Contractor: Resource Data International, Inc.
EPRI Project Manager: J. Platt

NUCLEAR POWER

EPRI Research Publications, Products, and Expertise in Maintenance
NP-7014 (Rev. 1) Final Report (RP2814-98); $200
EPRI Project Manager: R. Kannor

Passive Plant Natural Circulation BWR Core Studies
NP-7186-M Final Report (RP2660-57); $200
Contractor: GE Nuclear Energy
EPRI Project Manager: J. Yedidia

Investigation of Response Time Testing Requirements
NP-7243 Final Report (RP2409-5); $200
Contractors: Performance Associates, Inc.; Science Applications International Corp.
EPRI Project Manager: J. Weiss

Effect of Biofilms, Sunlight, and Salinity on Corrosion Potential and Corrosion Initiation of Stainless Alloys
NP-7275 Final Report (RP2939-4); $200
Contractor: University of Delaware
EPRI Project Manager: D. Cubicciotti

Reformulation of the LOMI Chemical Decontamination Reagent: Reduction in the Picolinic Acid/Vanadous Formate Ratio
NP-7276 Final Report (RP1329-3, -5); $200
Contractors: Niagara Technical Consultants, Inc., Bradtec Ltd.
EPRI Project Manager: C. Wood

Electrochemical Ion Exchange of LOMI Decontamination Solutions
NP-7277 Final Report (RP1329-6, RP2614-50); $200
Contractor: Bradtec Ltd.
EPRI Project Manager: C. Wood

An Approach for Evaluating Individual Plant Examination Insights
NP-7280 Final Report (RP3000-30); $200
Contractor: SAROS (Safety and Reliability Optimization Services), Inc.
EPRI Project Manager: R. Oehlberg

COMPBRN IIIE: An Interactive Computer Code for Fire Risk Analysis
NP-7282 Final Report (RP3000-39); $200
Contractor: University of California at Los Angeles
EPRI Project Manager: J. Sursock

Cathodic Protection Criteria for Controlling Microbially Influenced Corrosion in Power Plants
NP-7312 Final Report (RP2939-7); $200
Contractors: Corrosion Failure Analysis and Control; Florida Power Corp.
EPRI Project Manager: D. Cubicciotti

Applications of Probabilistic Risk Assessment
NP-7315 Final Report (RP3200); $200
Contractor: Yankee Atomic Electric Co.
EPRI Project Manager: J. Sursock

Design Guide for Fire Protection of Grouped Electrical Cables
NP-7332 Final Report (RP2969-4); $200
Contractor: Professional Loss Control, Inc.
EPRI Project Manager: J. Sursock

Proceedings: Main Coolant Pump Diagnostics Workshop—1990
NP-7335 Proceedings (RP1556-4); $200
Contractor: EPRI Nondestructive Evaluation Center
EPRI Project Manager: J. Weiss

Acid Sulfate Corrosion in PWR Steam Generators
NP-7346-M Topical Report (RPS407-36); $200
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: P. Paine

Radwaste Desk Reference, Vol. 1: Dry Active Waste
NP-7386 Final Report (RP2414-23); $1000
Contractors: Evergreen Innovations, Inc.; Right Angle Industries; Analytical Resources, Inc.; General Energy Systems
EPRI Project Manager: C Hornibrook

CALENDAR

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

OCTOBER

1–2
1991 FGDPRISM Training Workshop
Austin, Texas
Contact: Rob Moser, (415) 855-2277

1–3
Air Toxics Workshop: Assessing and Managing Risks
Pittsburgh, Pennsylvania
Contact: Leonard Levin, (415) 855-7929

1–3
Industrial Safety Innovations in Nuclear Power Plant O&M
San Francisco, California
Contact: John O'Brien, (415) 855-2214

1–3
Seminar: Gas Turbine Procurement
Danvers, Massachusetts
Contact: Henry Schreiber, (415) 855-2505

3–4
1991 FGDPRISM Training Workshop
Austin, Texas
Contact: Rob Moser, (415) 855-2277

7–8
Workshop: DSMANAGER Code Training
St. Paul, Minnesota
Contact: Steve Bubb, (612) 473-1303

7–8
Training Seminar: Demand-Side Management on Target—Concepts, Players, and Practices
Atlanta, Georgia
Contact: Larry Lewis, (415) 855-8902

8–11
1991 PCB Seminar
Baltimore, Maryland
Contact: Maureen Barbeau, (415) 855-2127

15–18
Meeting Customer Needs With Heat Pumps
Dallas, Texas
Contact: Pam Turner, (415) 855-2010

15–18
EMF Science and Communication
San Jose, California
Contact: Robert Banks, (612) 623-4646

15–18
International Conference on Power Quality: End-Use Applications and Perspectives
Gif-sur-Yrette, France
Contact: Marek Samotyj, (415) 855-2980

15–18
9th Particulate Control Symposium
Williamsburg, Virginia
Contact: Susan Bisetti, (415) 855-7919

16–18
Coal Gasification
San Francisco, California
Contact: Lori Adams, (415) 855-8763

16–18
Mutual Design: Transmission Lines and Railroads
Evanston, Illinois
Contact: Suzette Rius, (415) 855-2798

17–18
Workshop: CLASSIFY PLUS—Meeting Commercial Customer Needs
Portland, Oregon
Contact: Thom Henneberger, (415) 855-2885

22–23
Zebra Mussel Control Technology
Itasca (Chicago), Illinois
Contact: Barbara Evatt, (415) 855-2174

22–24
Power Quality Hands-on Training Course
Knoxville, Tennessee
Contact: Donna Eason, (615) 675-9505

23–25
8th Electric Utility Forecasting Symposium
Baltimore, Maryland
Contact: Phil Hummel, (415) 855-2855

29–November 2
Computer-Aided Control System Analysis
Birmingham, Alabama
Contact: Murthy Divakaruni, (415) 855-2409

NOVEMBER

4–6
International Conference: Managing Hazardous Air Pollutants
Washington, D.C.
Contact: Lori Adams, (415) 855-8763

5–6
Workshop: Cooling Tower Performance Prediction and Improvement
Eddystone, Pennsylvania
Contact: John Bartz, (415) 855-2851

5–7
Boiler Tube Failures in Fossil Plants
San Diego, California
Contact: Maureen Barbeau, (415) 855-2127

6–7
1991 Fuel Oil Utilization Workshop
San Antonio, Texas
Contact: William Rovesti, (415) 855-2519

7–8
Planning Your First Transmission Cable Project (Short Course)
St. Petersburg, Florida
Contact: John Shimshock, (412) 722-5781

12–15
Maintenance Proficiency Evaluation Training Course
Charlotte, North Carolina
Contact: Loran Maier, (704) 547-6152

13–14
Seminar/Workshop: Evaluation of Distribution Automation Systems
Dallas, Texas
Contact: Tom Kendrew, (415) 855-2317

13–15
Power Quality Hands-on Training Course
Knoxville, Tennessee
Contact: Donna Eason, (615) 675-9505

14–15
Workshop: CLASSIFY PLUS—Meeting Commercial Customer Needs
Charlotte, North Carolina
Contact: Thom Henneberger, (415) 855-2885

19–20
NMAC Workshop: Circuit Breakers
East Dundee, Illinois
Contact: Jim Christie, (704) 547-6053

19–21
Rotating Machinery Balancing: ROBAL
Eddystone, Pennsylvania
Contact: Tom McCloskey, (415) 855-2655

DECEMBER

2–6
Fireside Performance of Coal-Fired Boilers (Short Course)
Charlotte, North Carolina
Contact: Bob Leyse, (415) 855-2995

3–4
NMAC Workshop: Circuit Breakers
Middletown, Connecticut
Contact: Jim Christie, (704) 547-6053

3–5
Strategic Cost and Quality Management
Orlando, Florida
Contact: Susan Bisetti, (415) 855-7919

3–6
Symposium: SO_2 Control
Washington, D.C.
Contact: Pam Turner, (415) 855-2010

CONTINUED

CALENDAR CONTINUED

4–6
NMAC Workshop: Solenoid-Operated Valves
Clearwater Beach, Florida
Contact: Vic Varma, (415) 855-2771

10–12
Power Quality Hands-on Training Course
Knoxville, Tennessee
Contact: Donna Eason, (615) 675-9505

11–13
Training Seminar: Demand-Side Management on Target—Concepts, Players, and Practices
Phoenix, Arizona
Contact: Larry Lewis, (415) 855-8902

11–13
Workshop: Generators and Motors
Scottsdale, Arizona
Contact: Lori Adams, (415) 855-8763

12–13
NMAC Workshop: Circuit Breakers
Charlotte, North Carolina
Contact: Jim Christie, (704) 547-6053

JANUARY 1992

16–17
Workshop: CLASSIFY PLUS—Meeting Commercial Customer Needs
Dallas, Texas
Contact: Thom Henneberger, (415) 855-2885

29–31
Conference: Steam and Combustion Turbine Blading
Orlando, Florida
Contact: Lori Adams, (415) 855-8763

FEBRUARY

5–7
Computer Control and Automation
San Diego, California
Contact: Pam Turner, (415) 855-2010

6–8
Industrial Safety Innovations in Nuclear Power Plant O&M
Charlotte, North Carolina
Contact: John O'Brien, (415) 855-2214

MARCH

3–5
Seminar: Substation Voltage Uprating
Denver, Colorado
Contact: Joe Porter, (202) 872-9222

Authors and Articles


Alpert


Smith


Samotyj


Amarnath

The Promise of Conductive Plastics (page 4) was written by Taylor Moore, the *Journal*'s senior feature writer, with background information from **Seymour Alpert**, a senior member of EPRI's technical staff.

Alpert, now an executive scientist in the Office of Exploratory and Applied Research, came to the Institute in 1973 and has since served as technical director for a range of studies on synthetic fuels, renewable resources, and energy storage. Before he assumed his present role in exploratory research, Alpert served for three years as EPRI's first Research Fellow. Prior to joining the Institute, he worked for 15 years at Hydrocarbon Research and briefly at Chem Systems and SRI International. He graduated in chemical engineering from the Polytechnic Institute of Brooklyn and earned an MS in economics at Rutgers. ■

Problems With Power Quality (page 14) was written by Leslie Lamarre, *Journal* feature writer, with assistance from two EPRI staff members.

William M. Smith managed the Power Electronics and Controls Program in the Customer Systems Division from January 1989 until May of this year, when he became head of the new Product Delivery Enhancement Office. Before 1989, Smith managed research on demand-side planning. He joined EPRI in 1985 after eight years with Pacific Gas and Electric, ultimately as the supervisor of load management projects. Smith received a BS degree in physics and MS and PhD degrees in astrophysics from the State University of New York at Stony Brook.

Marek Samotyj, a senior project manager in the Power Electronics and Controls Program, came to EPRI as a consultant in 1984 and joined the staff a year later. Before that, he was a research assistant with the Energy Modeling Forum at Stanford University for three years. Still earlier, he held several consulting positions in Poland, including one with the Commission on National Economic Reform. Samotyj has BS and MS degrees in electrical engineering from Silesian Polytechnic University in Poland and an MS in engineering-economic systems from Stanford University. ■

Putting the Pinch on Energy Costs (page 24) was written by Peter Jaret, science writer, with assistance from **Ammi Amarnath**, a senior project manager in the Industrial Program of the Customer Systems Division.

Amarnath, who manages research on electrotechnologies for process industries, joined EPRI in January 1988. He had previously worked for seven years as a process engineer and supervisor for two manufacturers of process equipment, K-Sons Ltd. and Metito International. Amarnath holds BS and MS degrees in chemical engineering from the University of Mysore in India and the University of California at Santa Barbara, respectively. He also received an MBA from the University of Houston. ■

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