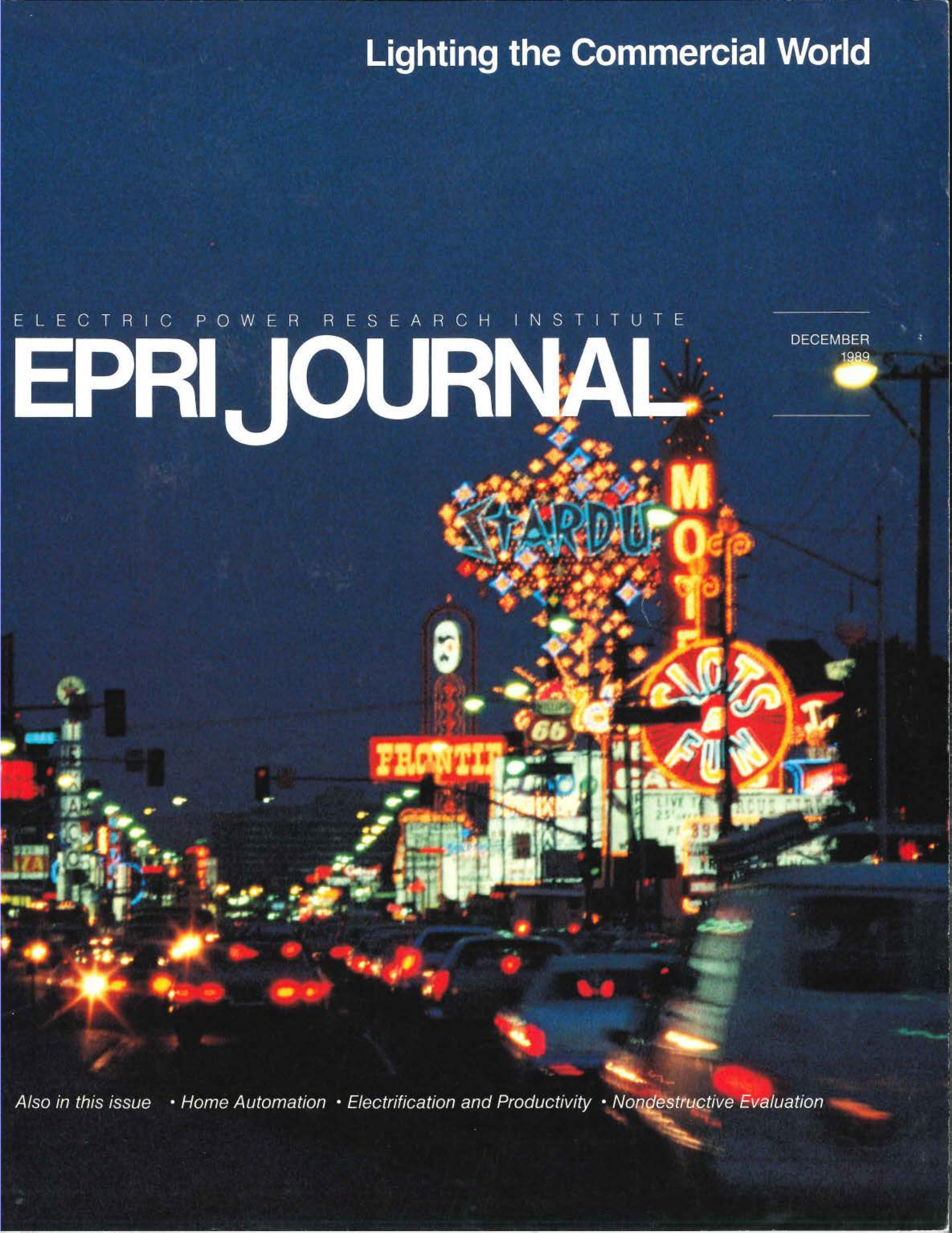
Lighting the Commercial World



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Also in this issue • Home Automation • Electrification and Productivity • Nondestructive Evaluation

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Cover: Lighting is often a key consideration for effective merchandising in the commercial sector. Unfortunately, many businesses do not see energy efficiency as an important concern in developing their lighting strategies.

Lighting for Efficiency and Productivity

In the current economic environment, efficiency is the order of the day. More and more U.S. businesses are feeling the pressure from foreign and domestic competitors to cut costs and increase productivity—to seize a competitive edge by doing more with less. Cost-effective improvements in energy efficiency and workplace productivity can make the crucial difference between a profitable commercial concern and a marginal one. Lighting is one area of energy use that offers a largely untapped potential for significant gains in efficiency.

Commercial buildings present a broad target for lighting improvements: lighting accounts for about a third of the electricity consumed in the commercial sector and can account for more than 40% of a building's peak demand requirements. Furthermore, lighting is often a major input to the cooling load, another important factor contributing to a building's energy use in summer peak demand periods.

Advanced lighting approaches can significantly boost efficiency in commercial settings—and, as this month's cover story notes, they can also enhance the productivity of a building's occupants. In fact, the productivity issue can override all others in the implementation of changes to the workplace environment, since labor costs exceed lighting costs by a ratio of more than 100 to 1 in a typical commercial enterprise. Although new lighting technologies clearly can provide energy savings for customers, changes in productivity must be valued as well.

The technology is here—there are many well-proven lighting measures and equipment upgrades that can be cost-effectively implemented today. These include more efficient lamps, ballasts, controls, and fixtures and improved ways of configuring and installing this equipment. The electric utility industry is working hard to get customers to use new lighting strategies to increase their operating efficiency. A majority of U.S. utilities have programs in place that educate customers on how to use lighting more effectively and that provide incentives for the implementation of cost-effective lighting measures and equipment.

EPRI is supporting these efforts by developing customer-oriented information that characterizes state-of-the-art lighting equipment and practices. The Institute is also demonstrating best-available technologies, developing lighting design tools, and performing evaluations of how lighting systems interact with other workplace support systems. Through these programs, we are striving to help utilities and their customers get the most value out of lighting energy use, and the best news is that there is value to be had on both sides of the meter. Utilities can select the lighting technologies that, if implemented by their customers, can best satisfy the utilities' load-shaping objectives, whether they be on-peak reductions, strategic load growth, off-peak sales, or retention of baseload. At the same time, customers will enjoy the benefits of lower energy costs and an enhanced work environment.

Morton Blatt, Manager
Commercial Program
Customer Systems Division

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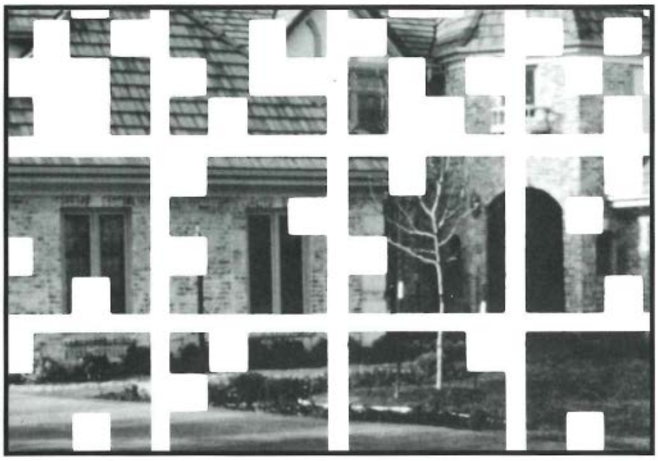

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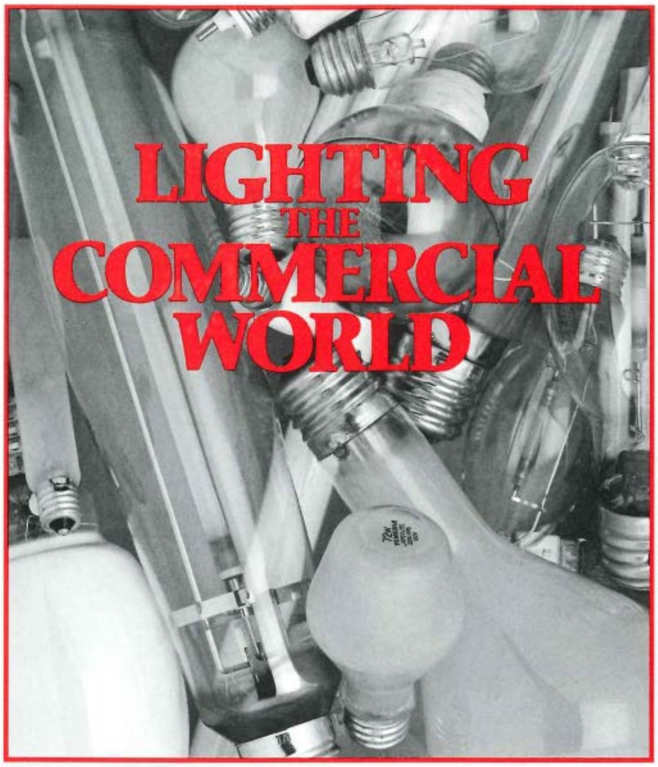

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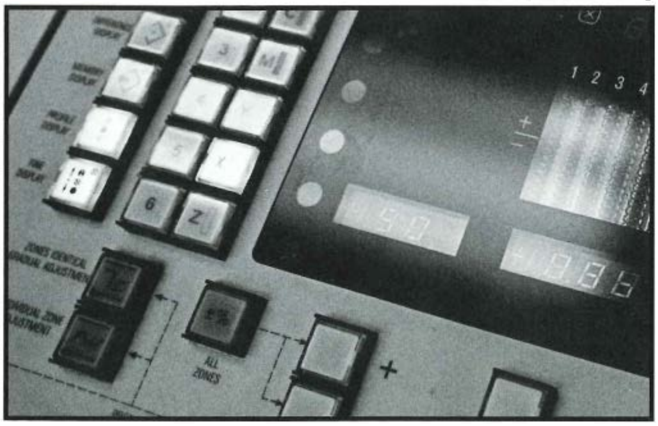
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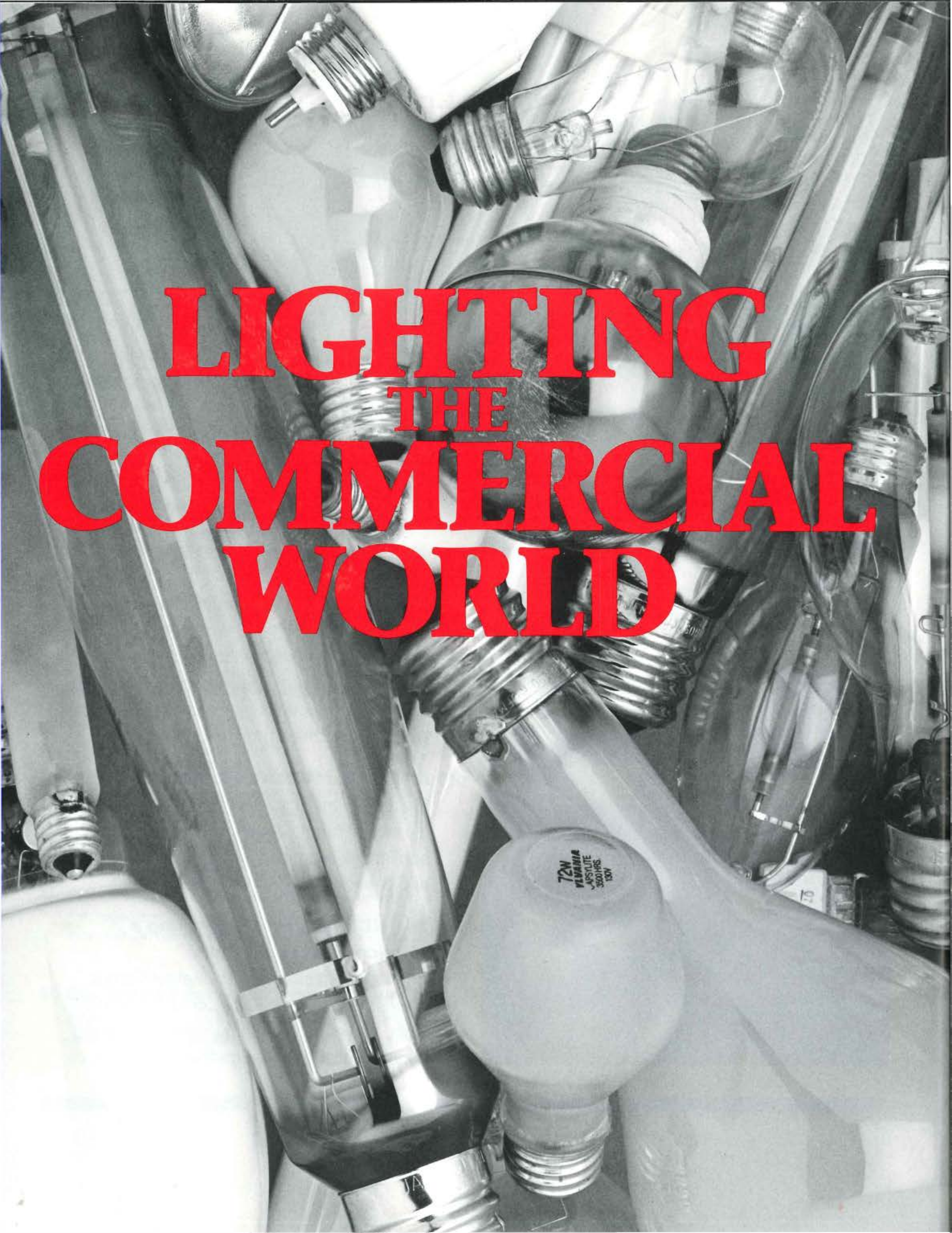
LIGHTING THE COMMERCIAL WORLD



For owners of the Peppermill Hotel Casino in Reno, Nevada, lights are serious business. They help maintain around-the-clock allure, keeping patrons comfortable and alert. As one manager puts it, "Lighting is key to the overall ambience we're trying to create for the customer." Understandably, then, a suggestion that the business install energy-efficient lights is no small proposal. But the Peppermill this spring did just that, replacing about 1000 incandescent bulbs with energy-efficient fluorescents that have cut the lighting bill in half. Even more important, the switch did not tarnish the dazzling atmosphere.

The retrofit project, done in collaboration with Sierra Pacific Power, was the result of a program designed to encourage energy efficiency in lighting. Utilities across the country today are offering similar programs. Many, like Sierra Pacific, attract customers with rebates for energy efficiency. Other utilities offer audits, loans, design assistance, and a variety of educational tools, including demonstrations of energy-efficient lighting options. But while these programs have helped encourage more efficient use of lighting, they have captured only a small portion of what some experts say is the largest potential for savings in any energy end use. And increasingly today, utilities are being called on to step up their efforts. Some conservationists go so far as to say utilities have both the responsibility and the clout to lead the effort to realize these savings.

"The invention of the light bulb gave birth to the electric utility industry, and utilities often have taken the lead in promoting high-quality, energy-efficient lighting," says Karl Johnson, EPRI project manager in Commercial Building Systems. "Certainly they have a good infrastructure to reach the consumer, and they've already taken advantage of it by offering incentives like rebates, audits, and loans. There's more that can be done. But a major challenge is to overcome

THE STORY IN BRIEF

With about a quarter of the electricity sold in this country used for illumination, industry experts believe that advances in lighting systems may have the largest potential for energy savings of any electricity end use. To help realize these savings, utilities across the nation have established programs encouraging their customers to adopt more efficient lighting. Targeting both new and retrofit markets, with emphasis on the biggest area of potential savings—the commercial sector—the programs offer incentives like rebates and loans for energy-efficient conversions. But stubborn barriers to customer acceptance persist, such as high first-cost expenses and confusion over the array of energy-efficient options available. A variety of energy conservation and lighting groups across the country, including utilities, are working hard to overcome these barriers. But just how much of an impact their efforts will have on the average utility customer remains to be seen.

the significant barriers to customer, designer, and builder acceptance of existing high-efficiency lighting products."

According to EPRI's statistics, lighting accounts for 20–25% of the electricity used in the United States. In the commercial sector, at least a third of the electricity used is attributable to lighting, and these figures would be even higher if the ventilating and air conditioning loads attributable to heat emitted by lights were taken into account. Various interest groups offer different estimates for the savings potential in lighting. But all agree there is tremendous opportunity for improvement, particularly in the commercial sector. "This has been a much-heated topic involving tremendous controversy and many exaggerations of savings potential," says Clark Gellings, director of EPRI's Customer Systems Division. "The vastly different estimates have made it difficult for researchers to know where to focus their attention."

In an effort to pool the input of the different groups, EPRI distributed a questionnaire on the maximum potential savings in efficient technologies and followed up with a workshop in April 1989. Gellings, who organized the workshop, believes this project represents the first time anyone has rounded up the calculations of such a diverse group of conservation experts. The resulting report cites a savings potential from adopting efficient commercial lighting technologies of 39–55% by the year 2000. The commercial lighting savings accounts for about 65% of the potential lighting savings in all sectors, including industrial and residential. The report incorporates the views of a wide range of groups, including the Natural Resources Defense Council, Lawrence Berkeley Laboratory, the Rocky Mountain Institute, public utility commissions, EPRI, and others.

Amory Lovins, director of research at the Rocky Mountain Institute in Colorado and an outspoken conservationist, calls the untapped potential in lighting "the biggest gold mine in the economy," saying efficiency improvements could save U.S. consumers billions of dollars a year because of the reduced cost of maintaining and operating more efficient systems. In other words, he says, "this is not a free lunch. This is a lunch you are paid to eat."

Utility involvement in promoting energy-efficient lighting over the years has been spurred by concerns about capacity, the potential environmental impact of new power plants, and a desire to help customers cut costs. During the energy crisis of the 1970s, utilities in California and the Northwest pioneered the movement to promote all kinds of energy efficiency. Now, the greatest momentum can be found in New England, where utilities are working hard to keep electricity demand during peak hours at a level comfortably below capacity. There environmental groups and utilities have found a common cause in conservation and are collaborating on strategic plans to control electricity demand. Meanwhile, utilities without immediate capacity crises are relying on such programs to help offset anticipated future increases in demand. Wherever they are implemented, strategies in lighting efficiency—which range from installing more efficient bulbs to using daylight to supplement electric light—are an effective way to help postpone building the next generation of power plants.

Utility concerns

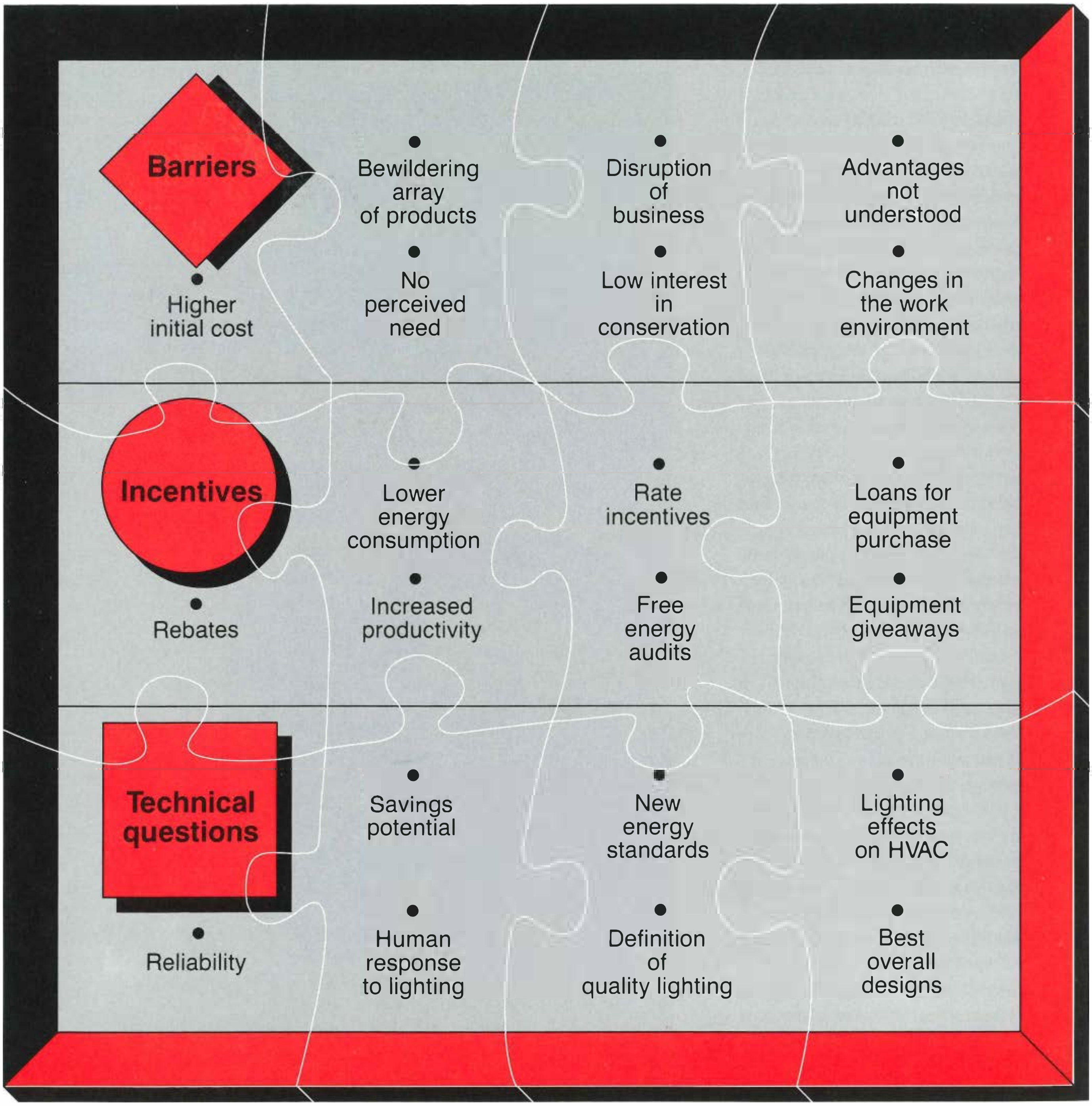
Even though lighting has been viewed as a captive market for electric utilities, innovation in making this end use more efficient is on the rise. EPRI's current commercial lighting research plan reflects this increased interest. The plan for 1989 and 1990 focuses new projects on peak clipping and other strategic conservation objectives, with the commercial sector as a prime target. Commercial lighting is one of the largest single contributors to peak demand at most utilities. For many, controlling demand through strategic conservation (a form of demand-side planning) is becoming increasingly more attractive than the traditional supply-side planning. Some utilities specifically gear their incentives toward reducing loads during hours of peak demand.

A 1987 EPRI survey showed that 60% of utilities surveyed used lighting for a wide range of demand-side management needs and 30% had lighting-efficiency programs in place. A separate study from the same year showed that the bulk (92%) of the energy-efficient utility lighting programs are directed toward commercial and industrial customers. Schemes ranged from incandescent-fluorescent conversions to installing occupancy sensors and daylight sensors. Financial assistance to the customer, including rebates for installing high-efficiency equipment and interest-free loans, was the most popular method of implementation (offered by 64% of the utilities). Energy audits (offered by 52%), most of which are free, was the second most common method, followed by studies evaluating new technologies (conducted by 12%). Another 12% of surveyed utilities provided education on effective and efficient lighting.

The number of utilities with such programs has increased in the years since the survey, mainly because of the new thrust in New England. And the National Association of Regulatory Utility Commissioners wants to encourage more utilities to follow suit. NARUC's conservation committee is working on making energy-efficiency programs more attractive for utilities. "Investor-owned electric utility companies, which supply 77% of this country's electricity, typically lose money when they help their customers use electricity more efficiently," says Stephen Wiel, chairman of NARUC's conservation committee. "State regulatory commissions currently set rates using formulas that reward utility companies for increasing sales. In an effort to help utilities profit from conservation programs, NARUC now is encouraging

Why Not Upgrade?

The simple availability of energy-saving lighting equipment has not been enough to spur its wide usage. For the commercial sector, the decision to implement advanced lighting systems can be seen as a complex puzzle of perceived barriers, incentives (many offered by individual utilities), and technical questions. Simplifying such decisions through continued research and innovative marketing could significantly increase customer involvement.



commissions throughout the country to experiment with ratemaking reforms. Among the suggestions is that utilities be allowed to earn a fair return on investment in energy conservation programs, just as they make money by investing in new plants. But more changes are needed, according to Wiel. Other incentives, such as bonuses for achieving conservation goals, are necessary to overcome the current disincentives, he says.

Only 10 states, including Wisconsin, currently allow public utilities to make a return on investment in conservation programs. An added incentive for Wisconsin Electric Power is a bonus for reducing peak megawatts. Wisconsin Electric's programs as a result have saved more than 156 MW—about 50% of which is from lighting—since the program started two years ago. That's enough to power about 78,000 homes. The program offers rebates based on the cost of the conversion, the kilowatts shaved from the utility's system peak, and the kilowatthours saved. "We're willing to kick in on just about anything reasonable the customer presents to us that'll improve efficiency," says Dan Thomas, supervisor of commercial and industrial energy management for Wisconsin Electric. One project involved installing about 175,000 electronic ballasts in the fluorescent lighting systems throughout Milwaukee's public schools, about 150 buildings in all. The $5 million project resulted in $2 million worth of rebates. The resulting energy savings will offset the entire cost of the job in five years.

For Consolidated Edison of New York, lighting and other conservation programs are attractive as long as the cost of saving a kilowatt remains lower than the cost of building a new kilowatt of capacity, says Steve Pertusiello, a manager in the conservation department. Consolidated Edison, which supplies power to a 660-square-mile area, including all of New York City, has offered incentives for lighting efficiency to commercial and

Getting the Word Out

Utilities often offer their customers special rates, loans, or other incentives to upgrade lighting systems as part of their energy conservation programs. Brochures educate customers about the incentives and hardware options available, and some utilities even give on-site design assistance to ensure that customers make the most of advanced lighting opportunities.

industrial customers for the past two years. Those with peak demands between 150 and 500 kW can have their systems audited free.

A separate, pilot program encourages customers to devise their own plan to reduce their lighting load and other energy loads that affect the utility's system peak. If the plan meets utility requirements, the customer will get a $200 rebate for every kilowatt reduced from peak demand, with a maximum offer equivalent to half the cost of the installation. Rebates are offered also for implementing energy-efficient technologies such as lamps, ballasts, occupancy sensors, and daylighting controls.

Pertusiello credits encouragement from the state commission. "They've been mandating programs and telling us which measures we should consider to offer for incentives," he says. But Consolidated Edison has another motivation as well. With supply options limited because of strong opposition to new plants, the only alternative is to control demand or to buy electricity from the independent power producers. Lighting conservation programs have also helped Consolidated Edison defer the expansion and upgrading of its distribution systems.

Somes utility programs go beyond retrofitting existing lighting systems to target the new construction market as well. For example, New England Electric System's "Design 2000" program targets new commercial and industrial buildings, which are expected to account for much of the utility's growth in peak demand in the next decade. Incorporating energy-efficient strategies during the initial design of a building is almost 10 times cheaper than retrofitting, according to New England Electric's calculations. The program, which is among the most sophisticated in the country, was developed in conjunction with the Conservation Law Foundation of Boston. It offers financial assistance, up to the full cost of upgrading to a more energy-efficient system; a design incentive of up to 6% of the New England Electric investment in the customer's project; and design assistance from a team of consultants. The utility also will work closely with customers, using a computer software program to determine the best energy-efficient options for a given building.

One "Design 2000" lighting project in the works involves a 200,000-square-foot computer company office building in Marlboro, Massachusetts. Timing controls and occupancy sensors that turn lights on and off automatically will be incorporated in the new structure. Energy-efficient fluorescent lamps and ballasts also will help save energy. The utility will spend up to $27,695 to cover the entire cost of the efficiency improvements.

Since the start of its systemwide programs two years ago, New England Electric has spent nearly $60 million on planning, implementation, and evaluation of conservation programs, about a third of which has gone toward lighting, reports Peter Gibson, manager of conservation and load management services. The resulting savings total about 110 MW. Gibson says that conservation programs typically are 30–50% less expensive than building new power supplies.

Barriers for customers

Convincing businesses that energy-efficient lighting can maintain and even enhance their environment is a challenging task. Even customers with significant lighting bills are hesitant to alter lighting systems that are functioning properly. Glenn McCormick, engineering manager for the Peppermill in Reno, says most casinos are more concerned about their appearance. "If your casino attracts one person who comes in regularly, that far outweighs any energy savings you're going to get out of changing a few light bulbs," he says.

For more typical commercial customers, the barriers are just as strong. Utilities like Consolidated Edison, which services a substantial number of tenant-occupied commercial buildings, find there is little incentive for either the tenant or the landlord to save energy. The landlord simply passes the energy bill on to the tenant, and the rent typically would not reflect any savings resulting from the tenant's efforts. Most commercial buildings, in fact, are not owner-occupied.

Peter von Herrmann, president of the Lighting Research Institute, which focuses on the human response to lighting, says productivity is another important concern. For example, von Herrmann says, the employee cost of a square foot of office space (assuming a salary of $40,000 and a 100-square-foot office) equals $400 a year. But the cost of lighting that square foot is only about 50¢ a year. If productivity is adversely affected even slightly by efficiency improvements in a lighting system, those changes will lose much more money than they ever could save in electricity. "We are saying that the productivity gain is a very important one. Or, at least, not losing productivity," von Herrmann says. "Otherwise, you're kidding yourself in the energy equation."

Richard Tempchin, a manager in the customer services and marketing division of Edison Electric Institute, says one key problem for utilities trying to "sell" the idea of energy-efficient lighting is that customers often are overwhelmed and confused by the number of options. "What's happening is the technologies are getting way ahead of customers," he says. "There are all kinds of new options—energy-efficient ballasts, electronic ballasts, dimmers, energy management controls. It's not as easy as it used to be to make these decisions in lighting." As Tempchin points out, commercial customers, who get a wide selection of equipment from lighting suppliers, are more informed than residential customers. Some of the more advanced lighting technologies simply are not available in hardware or grocery stores.

Strategies for the Old and the New

Energy-efficient lighting works well both with existing buildings and in new construction projects. Virtually all facilities can be retrofit with advanced hardware that will increase efficiency and improve lighting quality. Designers can be more comprehensive with new buildings, taking full advantage of daylighting and computer-based control strategies.

An additional obstacle is the first-cost expense of high-efficiency lamps. If a lighting bill is a small expense for the consumer, it is hard for that person to justify buying an energy-efficient fluorescent lamp when the standard incandescents are available at about a tenth of the cost. Some utilities have tried to overcome this barrier by actually giving lamps away. About four years ago, Texas Utilities tested the residential waters by sending out coupons for free efficient fluorescent bulbs that could be screwed into incandescent sockets. About 25% of the 16,000 residents in the targeted town took advantage of the offer.

John Nordgren, a supervisor in lighting for Puget Sound Power & Light, says Puget's programs have been successful specifically because they help cover the seemingly high first-cost expenses. Lighting has always been a significant part of Puget's programs, typically accounting for more than 40% of annual program expenses. Among the most successful of Puget's programs is one awarding grants that typically cover 50% or more of a customer's energy-efficient conversions. The utility also conducts audits for the customer, estimates the savings that would result from an energy-efficient system, and helps in selecting a contractor for the job. But no matter how attractive such programs may sound, they remain a challenge to sell, Nordgren says. "Some customers have been motivated from a motherhood and apple pie perspective, the view that saving energy is a good thing to do," he says. "But most are inspired by great savings." In addition to Puget's incentives, customers look for substantial dollar savings on their electricity bills. "Dollars," Nordgren says, "are the biggest motivators."

Karl Johnson of EPRI agrees. "If lighting's less than 1% of customers' overall costs, that's the kind of attention you can expect them to give it." Also, he says, as long as an existing lighting system functions adequately, the customer will most likely see no need to change it. But even if customers want to change their lighting, they often do not have the time to explore the multitude of efficiency options, Johnson says.

In his prior management experience with Stanford University, Johnson confronted many of these customer barriers. Nevertheless, he convinced the university to install more efficient lighting systems campuswide. He says it is important to be sensitive to the customer's concerns when proposing any project. "We approached this and other projects by proposing to *improve* the quality of the lighting system while saving money and energy. If I'd walked in and said 'I'm going to de-lamp your fixtures,' they would have hit the ceiling." Part of the Stanford project involved replacing about 500 incandescent lamps in the law school with screw-in fluorescents and reflectors. This saved about 75% of the lighting energy used in the original system and improved the environment.

Technology transfer

Getting information on lighting to those who are not necessarily interested in efficiency is even more important than developing new technology, some experts say. "There are so many high-efficiency products already available that customers aren't using now," Johnson says, offering the electronic ballast as one example. "It is important to provide information on existing technologies while developing the even more advanced technologies."

Among technology transfer efforts currently under way is Seattle City Light's design laboratory. The 8500-square-foot facility, which opens officially in December 1989, is geared toward engineers, architects, lighting designers, contractors, manufacturers, equipment suppliers, and their clients. The design laboratory will allow visitors to test or demonstrate energy-efficient lighting strategies in mock commercial settings.

One feature of the new lab is a demonstration area with walls, ceilings, and furniture that can be altered to mimic an actual setting. Strategies for daylighting—the use of natural light to supplement interior electric lighting—also can be tested in full-sized commercial environments. A resource library will provide the latest information on efficient lighting technologies. In a preliminary report, Seattle City Light identified the commercial sector as the fastest-growing electricity consumer in the Northwest. In addition, the report says, lighting accounts for more than half of commercial electricity, when heating, ventilating, and air conditioning loads are figured in. The project cost $1.9 million, 70% of which was funded by the Bonneville Power Administration.

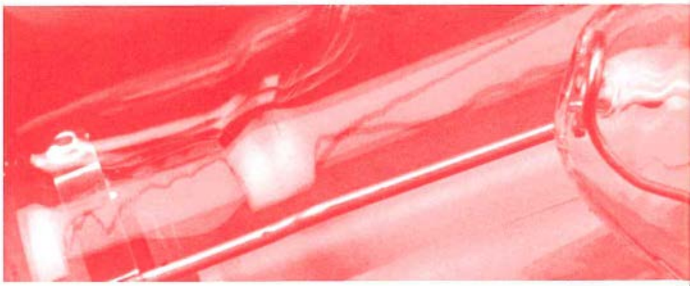
Meanwhile, the New York State Energy Research and Development Authority is working on plans to establish a similar center in New York. Many lighting manufacturers and some utilities provide similar demonstrations. But planners involved in the Seattle and New York centers say their demonstrations are more comprehensive and do not limit technology to one manufacturer's products. David Goldstein, senior staff scientist at the Natural Resources Defense Council, believes lighting labs like Seattle's should be in every major city in the country if the United States is to begin to take advantage of the savings potential in lighting. But others question the effectiveness of such centers.

"You often have the problem of bringing the customer to the mountain versus bringing the mountain to the customer," Johnson says, suggesting that such centers could be more effective if they incorporated mobile exhibits. Johnson's concern is that most lighting systems are not designed by professional lighting designers—the people likely to make most use of demonstration centers like Seattle's. Meanwhile, those less skilled in lighting design still have not been reached. An EPRI study has determined the need for a mobile unit and created specifications for a unit that could demonstrate a variety of lighting systems. The module, as specified, would be freestanding, so utility personnel could assemble it to fit a variety of commercial and other settings.

Other efforts in technology transfer are under way elsewhere. Currently in the works at the year-old Lighting Research Center at Rensselaer Polytechnic Institute in New York are plans for a research, education, and technology transfer program. LRC, which evolved from a need identified at an EPRI workshop five years ago, is striving to become a national center for lighting research and design. It stresses an interdisciplinary approach, pooling the knowledge of specialists in fields ranging from psychology to computers. LRC has proposed a project that will investigate impediments to technology transfer in the marketplace and assess how well utility programs are working, says Associate Director Russell Leslie. Officials there still are working to secure funding for the project.

The program would include a symposium to address the technology transfer issue. The aim is to bring together an assortment of people involved in decisions on lighting, including designers, manufacturers, utility representatives, engineers, and vision scientists. "All these different groups really have trouble talking to one another," Leslie says. "Yet each group is putting forth information that is vital to the functioning of the other groups."

The spearhead of the LRC technology transfer program would be *Lighting Now*, a serial publication to be developed to reach people from the whole range of related fields. The proposed format is a four-page, biweekly bulletin that could be kept in a binder for reference. LRC plans to develop an international communication network to keep abreast of the latest developments in lighting around the world. Currently, Leslie says, information on such developments may not appear in professional journals until



The options available for improving lighting efficiency today can be overwhelming at times, not only for the consumer but also for the utility. The potential for improvement does not stop with more efficient lamps. It is found also in ballasts, in fixtures, in lighting-control strategies that may incorporate the use of natural daylight, and in the complex interactions between the lighting and heating, cooling, and ventilation systems.

To take advantage of the full potential for savings while maintaining visual quality, experts suggest that utilities adopt programs that integrate a number of efficient technologies. Here is a sampling of some relatively new, highly efficient lighting technologies. It is by no means a comprehensive list but highlights effective technologies that have not yet been adopted widely.

Compact fluorescent lamps Twin-tube and quad-tube fluorescents, two of the several types of compact fluorescent, are often used to replace incandescent lamps. Some are made to be screwed into existing incandescent fixtures. They are available in wattages ranging from 5 to 26 and offer wattage savings of 60–75% when used to replace incandescents. They last about 10 times longer than incandescents but can cost up to 20 times as much. The payback period can be less than a year, depending on use and energy rates. Advancements in phosphors—the white coatings inside fluorescent lamps that emit visible light when exposed to ultraviolet radiation—have made the color quality of fluorescents virtually indistinguishable from that of incandescents. Compact fluorescents are made both with and without ballasts attached.

Incandescent lamps Significant improvements have been made in incandescent lamps, including the development of elliptical reflector (ER) lamps for recessed fixtures and improvements in the reflective films on the walls of other incandescents. The elliptical shape of ER lamps, combined with an internal coating of reflective aluminum, directs light downward rather than into surrounding areas. Other incandescents now are made with films on the interior lamp walls that reflect infrared light onto the filament while allowing visible light to pass through. The formerly wasted infrared energy then heats the filament further, producing more visible light. The bulb shapes have been changed to both spherical and cylindrical to help the films reflect the infrared light properly. A 60-watt coated incandescent lamp provides about as much light as a conventional 150-watt incandescent PAR lamp. ER lamps are widely available, but as of

Lighting Technology

now only one manufacturer has introduced incandescents with selective reflecting films.

T-8 fluorescent lamps The 4-foot, 32-watt T-8 lamp has a double phosphor coating, which offers higher efficiency, longer-lasting brightness, and good color quality. With a diameter of 1 inch, it is half an inch thinner than the T-12 lamp, which it typically replaces. The T-8 lamp will fit into the standard 4-foot fixture but will not work with a T-12 ballast. With an electronic ballast, the lamp operates at a higher frequency, making it more efficient. When the lamps are compared without ballasts, the T-8 proves to be about 12.5% more efficient than the standard T-12 lamp.

Low-wattage metal halide lamps Metal halide lamps, a type of high-intensity-discharge (HID) lamp, have traditionally been available only in wattages between 175 and 1000. Now available in 100 watts or less, they can be used to replace incandescent lamps. While compact fluorescents typically replace incandescents of 100 watts or less, HID lamps are used in place of the higher-wattage incandescents. Like incandescents, metal halide lamps allow for better focus and control than fluorescents in that they cast light directly toward one point, rather than to a general area. HID lamps are 150% more efficient than standard incandescents. They are just beginning to replace incandescents in the commercial sector for uses like display lighting.

Electronic ballasts By far the most significant development in ballast technology, the electronic (solid-state) ballast runs fluorescent and HID lamps at high frequency. The result: essentially no flicker or noise and lower ballast power losses. With fluorescents, increased efficiency is an added advantage. For example, a standard T-12 system with an electronic ballast is up to 25% more efficient than a T-12 system with a standard, magnetic ballast. With HID lamps, electronic ballasts allow more control over light output during the lamp's life. Some electronic ballasts offer continuous, or step, dimming capability, allowing light to be adjusted to the requirements of a particular space. With electronic ballasts, single lamps can be dimmed as easily as large groups, making possible more options for lighting control strategies such as daylighting.

Optical reflectors Made of aluminum, silver, or multiple dielectric coatings, optical reflectors improve the efficiency of fluorescent fixtures by up to 20%. The reflectors direct more light downward so that it does not bounce around inside the fixture. Such reflectors can cut lighting energy costs for existing overlighted spaces by half because they make it practical to remove half the lamps and ballasts from a fixture; the decrease in light output from that fixture is only 25–30%. The aluminum reflectors offer the lowest initial cost; the silver and dielectric film types have the highest reflectivity. The multiple dielectric coating also can be used on HID fixtures and has been shown to increase the efficiency of such fixtures by up to 30%.

Occupancy sensors and photocell controls These are just two examples of the types of technology being used to control lighting in commercial buildings. Occupancy sensors use infrared or ultrasonic signals to detect motion in a room, automatically turning lights on when motion is detected or off when none is detected. Photocell systems detect the amount of daylight entering a given space and automatically adjust the electric lighting system to maintain the desired illumination. Computer-controlled lighting management systems that incorporate several control strategies also are being used in the commercial sector. Such systems have included functions that turn lights on and off at programmed times, automatically reduce lighting loads during times of unusually high peak utility demand, and increase power to a lighting system as it dims with age and dirt accumulation. □

Research at EPRI

EPRI research has explored many aspects of energy efficiency in lighting. In the process, it has developed a broad portfolio of tools and information of value to utilities, including technology assessments, surveys of utility lighting incentive programs, design and analysis software, retrofit strategies, and a utility lighting handbook. Two recent projects have produced particularly interesting results bearing on the design of energy-efficient lighting systems.

In the first, EPRI and the Department of Energy (DOE) have been collaborating on a project to find design strategies that help optimize the interaction between lighting systems and heating, ventilating, and air conditioning (HVAC) systems in commercial buildings. Improving this interaction not only can help save energy but also can reduce peak demand for utilities, particularly during the summer months, when the heat from lights creates more work for air conditioning systems.

The project has already involved more than 350 tests in a fully instrumented test chamber at the National Institute of Standards and Technology (NIST). Data have been gathered on some 400 variables that relate to lighting levels, air temperatures, room surface temperatures, and other factors. A computer model of the chamber is being developed for future use in improving lighting and HVAC designs.

One of the successful strategies tested to reduce peak load entailed controlling the temperature in the return air plenum to keep it a few degrees cooler than is typical, and then allowing the temperature to rise a few degrees during the building's peak demand period. Understanding and controlling such interactions can reduce peak demand due to lighting, cooling, and fans by about 17%. If these more efficient strategies were applied to just 5% of existing U.S. commercial spaces and 25% of new construction each year, demand reductions would total about 1400 MW annually.

Researchers will continue testing and validation of the new design methodologies and computer model and will work with the design community to adopt these improved methods.

In an effort to better understand the human impact of various lighting systems, EPRI joined with the New York State Energy Research & Development Authority, DOE, NIST, and the Lighting Research Institute in funding additional analysis of an earlier DOE study. This "second-level," follow-up analysis thoroughly examined 912 workstations in 13 U.S. office buildings. Extensive data were collected on energy use as well as lighting levels and the contrast between light and dark areas throughout the workstations. Occupants also responded to a questionnaire asking them, among other things, to rate the lighting available for specific tasks and in the surrounding environment. Participating occupants had been at their workstations at least one year.

This study indicated that lighting satisfaction is strongly correlated with the distribution of light. Cases with uniform distribution provided more satisfaction than cases with strongly nonuniform patterns, which were produced by some systems using task lighting. Some systems with task lighting tended to use greater power densities; thus the belief that individual task lighting combined with lower general (ambient) lighting is always energy efficient and advantageous was not borne out by this analysis. The reason may be the extreme contrast between the task lighting and the darker surrounding vertical surfaces of the workstations studied. Another key finding of this study was that there was little or no correlation between lighting power densities and occupant satisfaction with the lighting system.

Overall, the study provides valuable insights on different types of lighting systems and the need to carefully understand the complex impacts of lighting systems and design strategies on occupant satisfaction. Additional research topics identified by this study are being evaluated for further investigation. □

years after the work has been done. Another problem is that the information presented is so highly technical that only a limited audience can understand it. "You have to get that information to the people—the building managers, the architects, the electricians, and all the others who specify lighting. That's exactly what we're trying to catalyze here. No one is doing that effectively now."

Standards and quality

Another avenue for encouraging efficient lighting is to impose standards that mandate or suggest maximum energy levels, in watts per square foot. To an industry outsider, this may sound like a simple solution. But maintaining quality while encouraging efficiency is no easy task. A specified maximum energy use does not guarantee good-quality light. Lighting quality depends on a number of factors, including color rendition and glare.

Jim Heldenbrand, manager of standards for the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), admits that standards have limitations. "You cannot set standards that only the best design can meet," he says. "You have to set standards that, in essence, eliminate the poorest practices only." It has taken six years for ASHRAE and the Illuminating Engineering Society of North America to develop the so-called 90.1P standards aimed at new commercial buildings. The voluntary standards got preliminary approval this summer and should be published by the end of the year. The lighting specifications are based on watts per square foot and are about twice as stringent as the previous standards. The Department of Energy in July imposed its own set of standards, which are mandatory for new federal buildings. Based on research that went into ASHRAE's standards, DOE's standards follow a similar format, allowing, for the first time, credit for daylighting and controls. DOE's standards also include even more stringent requirements for 1993.

But while the standards offer some guidance, the ultimate decision on fixtures and lamps still rests with the lighting designer. "Everyone in the scientific community and in the lighting industry will agree on one statement," Heldenbrand said. "There is no scientific measure for quality of lighting. And there is a strong need for this." Until such a measure is discovered, he says, decisions on quality will depend primarily on the professional judgment of lighting experts.

In the meantime, though, the federal government has adopted an amendment to the 1987 National Appliance Energy Conservation Act that requires fluorescent lamp ballasts in this country to meet specific efficiency levels. As of January 1, 1990, manufacturers will be prohibited from producing the least-efficient types of ballast currently on the market. The new law also bans the importation of inefficient ballasts.

It is almost impossible to determine how well utility programs address the issues of quality in lighting. But ambitious programs like New England Electric System's "Design 2000" emphasize providing a "high-quality environment through reduced glare, better color rendition, and lighting controls that are more responsive to occupants' needs." Feedback from other utilities shows that customers now rely on them to help make decisions regarding quality. "Customers will call us up asking our opinion on some fixture, some bulb, or some technology in general," says Dan Thomas of Wisconsin Electric Power. "They're using us as a sounding board."

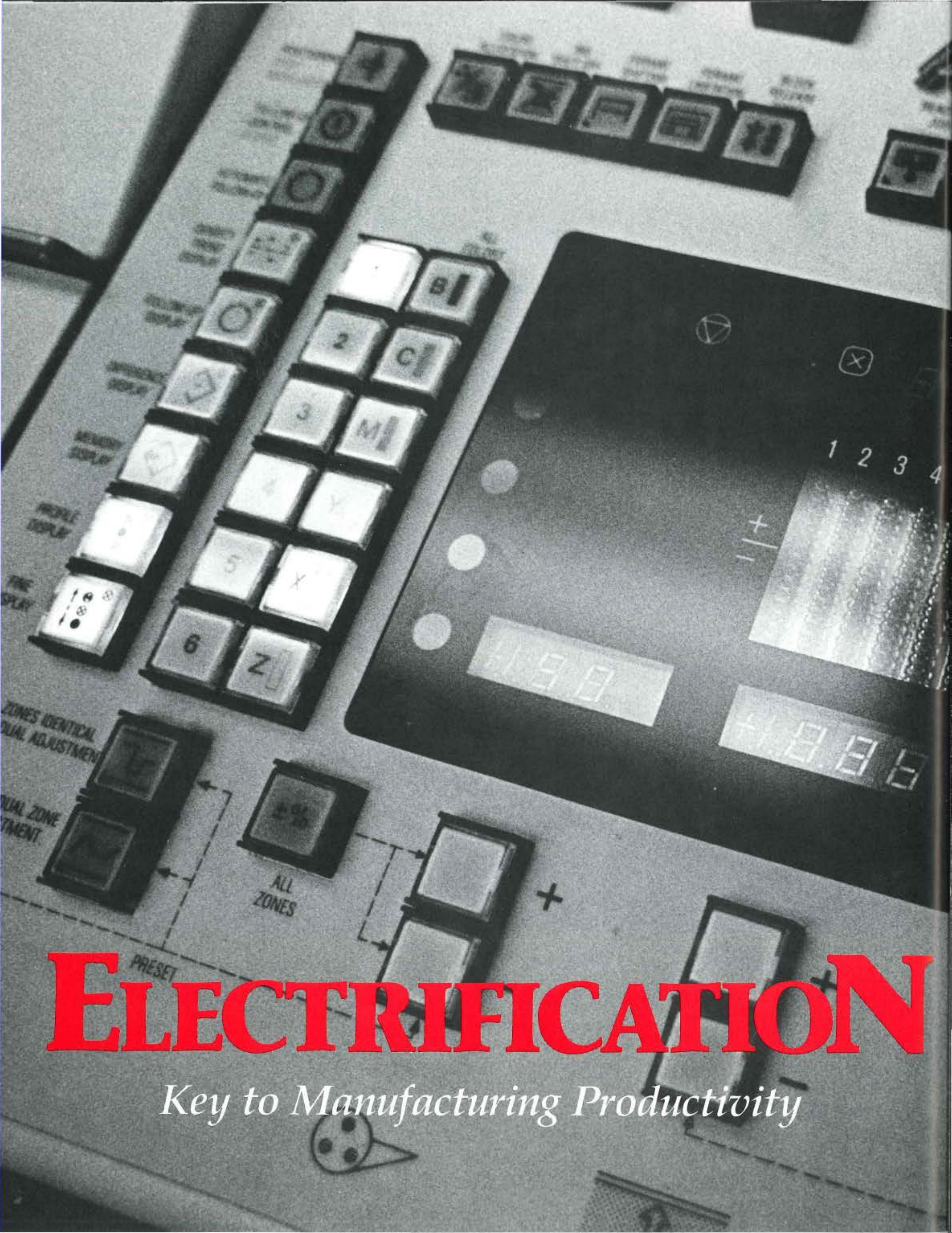
Bob Henderson, senior commercial program specialist at Carolina Power & Light, stresses that today's working environment calls for closer attention to quality in lighting. Lighting schemes must be designed for what he calls "seeability"—the ability to see well. Modern office equipment has introduced new complications, such as glare on video display terminal screens. When a break room at Carolina Power was converted into a stenographers' office, workers complained that glare from the light fixtures interfered with their attempts to read from computer screens. A big part of the problem was that the office was overlighted. Among other changes, two lamps were removed and one ballast was disconnected from each lighting fixture. Acrylic lenses were replaced with half-inch parabolic-wedge louvers, and sun screens were installed on windows. There was little or no reflection and the lighting energy bill was cut in half.

Future work

Technological advances in lighting are improving the quality and efficiency of lighting every year, making options for utilities and their customers even more abundant. Perhaps the best peek into the future is offered at Lawrence Berkeley Laboratory (LBL), where researchers are developing technologies ranging from new film coatings for windows that allow more effective use of daylighting, to a new, high-frequency surface-wave lamp that is 30% more efficient than the common fluorescent. One recent development could be useful to utilities as a design tool to optimize indoor and outdoor lighting. This tool, a software program called RADIANCE, simulates actual lighting environments so that quality energy-efficient lighting systems can be designed from the desktop. The simulations are so precise they resemble photographs. A user's options are virtually unlimited, including the ability to move or change fixtures and furniture. The program uses a simulation technique called backward ray tracing, by which a researcher can track a light path from its destination to its source, incorporating such factors as specular reflection and geometry. The program has been verified with real-life measurements. LBL has released this research-grade program to universities and hopes to make it more user-friendly in the future.

But while such technological advances may sound exciting, they also raise some serious questions: Will the marketplace ever begin to keep pace with this technology? What will it take for that to occur? Perhaps increased utility activity is part of the answer. But clearly the success of energy efficiency in lighting won't depend on utilities alone. It will depend on the efforts of other interest groups, the success of technology transfer, and—perhaps most important—the customer, be it the casino manager or the supermarket owner. As Arnold Fickett, vice president of EPRI's Customer Systems Division, puts it, "The guy who owns Joe's supermarket isn't going to worry at all about the next power plant. He's going to install more efficient lighting if he gets something out of more efficient lighting. You really have to think about what's in it for Joe." ■

This article was written by Leslie Lamarre, science writer. Technical information was provided by Karl Johnson and Morton Blatt, Customer Systems Division.



ELECTRIFICATION

Key to Manufacturing Productivity

Constantly rising productivity has supported the nation's phenomenal rise in living standards during this century. Creating ever more output with less input per unit is the magic that has allowed Americans to live well at home and dominate international markets. About half of the steady gains in U.S. manufacturing output since 1899 can be attributed to growth in multifactor productivity, a measure tracking the amount by which output exceeds the combined input of labor and capital. This single statistic reflects the enormous importance of productivity improvements to sustained economic growth.

The slump in productivity growth that began in the 1970s was thus a source of great concern. By the end of the decade, productivity growth in U.S. manufacturing had slipped into the minus column (–0.6% average annual growth), a disquieting contrast to the 2.2% average annual growth rate of the 1960s. Today productivity seems to be on the mend, at least in manufacturing, but caution lingers as the 1990s begin.

A forthcoming book by Sam H. Schurr, Calvin C. Burwell, Warren D. Devine, Jr., and Sidney Sonenblum, prepared under the auspices of EPRI's Energy Study Center, provides some critical background on the productivity problem and important clues as to the future. *Electricity in the American Economy: Agent of Technological Progress* proposes a way of looking at productivity and related issues as they are affected by the use of electricity.

The new work builds on a widely accepted economic view of the factors accounting for long-term productivity growth. Ever since the Industrial Revolution, when the steam engine first eased the load on groaning muscles, it has been known that capital investment in new machinery could increase output per worker. Careful economic studies by the Nobel laureate Robert Solow, Moses Abramovitz, and others have documented the fact that this gain is not merely a tradeoff, a substitution of capital for labor, but a true net increase in output over the com-

THE STORY IN BRIEF

A historical review of American manufacturing shows a strong linkage over the past century between technological progress and electrified production techniques. As centralized, steam-powered belt-and-shaft drives of the late nineteenth century gave way after World War I to decentralized electric motor drives mounted on individual pieces of factory equipment, American manufacturing productivity soared. A surprising concurrent decrease in energy intensity, even at this early stage, points up a key conclusion: electrification of processes allows manufacturers to do more with less—including less energy. Will another productivity breakthrough result from the present use of programmable automated controls? Although productivity trends faltered with the economic disturbances of the 1970s, the most recent developments in electronics—including sophisticated microprocessor technology for flexible, decentralized control—are expected to reestablish significant gains in manufacturing productivity in the 1990s.

bined input of capital and labor. The source of this surplus is rising productivity—the ability to do progressively more with less input per unit.

What, then, accounts for productivity growth itself? An important factor on which economists focus is technological progress, mainly as embodied in new plant and equipment and in new ways of organizing production.

Schurr and his colleagues begin where earlier works leave off, with a closer look at the nature of additions to capital stock and organizational changes in manufacturing, in particular as they have been influenced by the use of electrified techniques of production. The authors rely on two streams of information: historical descriptions of the evolution of manufacturing technology over the course of the twentieth century, and quantitative measures of manufacturing outputs and the productive inputs of labor, capital, and energy over the same period. This evolutionary perspective permits them to identify the underlying trends that characterize the long-term record.

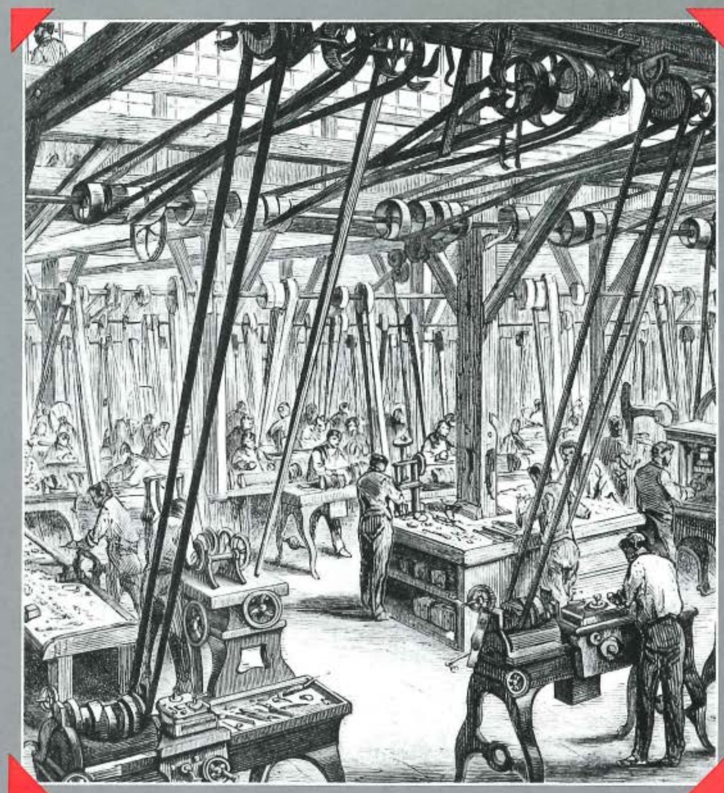
Some provocative patterns emerge. During the twentieth century, for example, the use of electricity in manufacturing has grown far more rapidly than any other input: at an average rate of over 8% annually, compared with 1.5% for nonelectric energy, 1.3% for labor, and about 3% for capital. These figures strongly suggest that additions to the capital stock in manufacturing have been geared predominantly to the use of electricity.

What the new study adds to the existing productivity-technology paradigm is a critical link between technological progress and electrified production techniques. In particular, this analysis is able to relate the ongoing process of electrification to steady productivity gains in U.S. manufacturing during most of the century, and to some surprising energy savings as well.

But how does electrification actually spur productivity? Returning to the focus on capital stock as the entry point for new technology, why has the investment in electrified equipment been so important? A

Industrial Energy Puts On a Clean Shirt

Electricity came into U.S. factories as a clean substitute for the coal-fired steam engine, mainly in printing plants and textile mills. But manufacturing operations still featured a central prime mover, rigid arrays of line shafts and pulleys, with leather belts delivering power to parallel ranks of machines. American society was slow to change, too. We remained horse-drawn and wood-fired, unpaved and tree-shaded.



partial answer is that the use of new electrical equipment has provided greatly improved ways to effect physical and chemical changes in materials. But of even greater importance is the fact that electrification has brought about changes in the organization of entire systems of production. A look at two critical developments in the history of American manufacturing shows the fundamental importance of these electrically based systemic changes.

Machine drive goes electric

The introduction of electric power into the American factory around 1890 triggered changes that eventually led to an explosion of productivity, but not in one giant step. Initially, electricity was treated as just another source of heat and power to supplement steam and other power sources. Its larger potential was not yet clear.

In pre-electric factories, machines had to be arranged in long rows parallel to the constantly rotating metal shafts that brought them their power. The shafts were driven from a central source, typically a coal-fired steam engine, which turned them continuously from dawn to dusk, no matter how many machines were actually in use. A large plant might contain thousands of feet of metal shafts and leather belts connecting shafts and machinery, as well as thousands of drip oilers suspended above the works for continuous lubrication. Just one broken shaft could halt work on an entire floor, and a broken steam engine could shut down an entire factory.

The initial innovation in the electrification of machine drive was to replace the central steam engine with a large electric motor. This first occurred in such industries as printing and textiles, where the grime from coal-fired steam engines was a constant threat to product quality and the need for clean power made it worth the risk to try a new technology. In textile mills, large motors of several hundred horsepower were soon driving over 1000 looms at a time. But the system of power distribution within the factory remained the same. Machines were still fixed to an elaborate over-

Electric Motors Reinvent the Factory

The unit drive, an electric motor at each machine, was conceived at the turn of the century, proved in World War I, and swept the nation in the 1920s. Materials could move more efficiently, and productivity soared as electricity's precision boosted throughput, cut losses, and even reduced energy intensity. U.S. lifestyles went big-time, the culture went ragtime, commerce climbed up skyscrapers, and everyone stepped on the gas.

head structure of shafts, clutches, belts, and pulleys.

A much more radical step was to outfit each machine with its own electric motor—that is, to use electrified unit drive, a development that did not take hold on a wide scale until after the First World War. Machines, freed from their overhead tethers, could be arranged in new ways—ways allowing related operations to be placed side by side, for example, to achieve a smoother work flow and a faster rate of throughput. These more efficient arrangements, plus the instant availability of electric power throughout the factory, permitted a new emphasis on continuous production, and output began to soar. In observations on some pioneering installations, Professor F. B. Crocker noted the importance of unit drive as early as 1901, long before it was widely used: "...the output of manufacturing establishments is materially increased...by the use of electric driving...with the same floor space, machinery, and workmen. This is the most important advantage of all, because it secures an increase in income without any increase in investment."

Dismantling the overhead structure cleared up headroom in the plant and allowed the introduction of traveling electric cranes for more efficient materials handling. Belt slippage, a major problem with line drive of multiple machines, became minimal with individual units. Unit drive eliminated power losses due to friction in rotating shafts, and it saved the energy that had been wasted in turning shafts when some machines were not in use. A malfunctioning motor stopped only one machine, not a whole group or a whole factory. Savings such as these were sometimes more than enough to offset the capital costs of additional electric motors, and beyond them were the enormous increases in productivity that resulted from the reorganization of production flows.

Productivity surges

The great productivity harvest in manufacturing came in the 1920s, a period that capped many years of growth in the use of electrified unit drive. During that decade, electricity use surged at an annual rate of more than 9%. But even more significant as a manifestation of the triumph of electric machine drive was the electrification of capital during that period: electricity use grew at a rate 13 times that of capital, whereas the use of nonelectric energy actually declined.

Accompanying this electrification was a surge in productivity. Gains galloped along at an average 5.2% per year during the 1920s, the highest rate for any decade in this century and a sharp contrast to the 0.8% average annual rate during the period 1899–1920. By correlating historical accounts with quantitative data, these gains can be traced in large part to the transformation in production systems made possible by electrified unit drive.

Paradoxically, the move toward electrification also coincided with a sharp decline in the intensity of energy use in manufacturing (the ratio of total energy input to manufacturing output). While productivity soared during the 1920s, energy use relative to output plummeted; the average rate of decline was 4.3% per year. How could such energy savings occur, given the losses that accompany the conversion of primary fuels to electricity? Indeed, it could be expected that a growing reliance on electricity in manufacturing would lead to the use of more, not less, total energy.

Electricity's role as an agent of technological progress provides the key. Just as electrified production techniques have allowed manufacturers to produce a given level of output with less input of labor and capital, so too has less energy input been required. Conversion losses of primary energy are more than offset by the greater efficiency of electrified production techniques. Electrified processes have allowed manufacturers to do more with less—including less energy.

Energy conservation, then, is neither an invention of the 1970s nor necessarily the product of deliberate striving. The decline in energy intensity associated with the adoption of electrified unit drive during the 1920s was stronger, in fact, than the decline during the 1970s, and it occurred without the prompting of a severe energy shortage. The average decline of 4.3% per year for the period 1920–1929 compares with about 2.4% per year for the period 1973–1981 (although the rate of decline increased in the early 1980s). These figures suggest a new way of looking at energy conservation: from this perspective, conservation over the long term is primarily a by-product of technological progress and the rising productivity it provides.

Overall, then, three major trends stand out: a growing share for electricity in the energy mix, rising productivity, and declining energy intensity. Typical of U.S. manufacturing during much of the twentieth century, these trends were all strikingly pronounced during the rapid change sparked by the rise of electrified unit drive in the 1920s.

Microprocessors bring flexibility

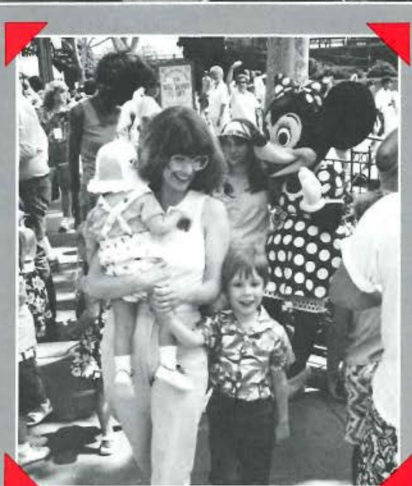
The need for flexibility in manufacturing continued to grow over subsequent decades. Eventually, another electricity-based technology emerged that would go beyond the flexibility of unit drive and trigger another breakthrough in the organization of production systems. That technology was the microprocessor.

While the electric motor provided the motive force to operate production equipment, the microprocessor has become the key to controlling it. Just as the electric motor managed energy with a precision and flexibility never before possible, so the microprocessor now manages information. Electricity and the microprocessor have become the new production partners, playing the same critical roles played by electricity and the electric motor earlier in this century.

Pre-electric control systems were crude, relying on mechanical gears or hydraulic devices to control machine tools. These early automatic machines of the 1920s were inflexible: only a limited and fixed sequence of control movements could be

Microprocessors Decentralize Production Control

Computers have maximized the power and precision of our manufacturing muscle, and microprocessors are now adding the versatility of distributed electronic intelligence—making available the full range of market, material, inventory, design, assembly, backlog, cost, and other information needed to customize production and maximize productivity simultaneously. Thanks to the unique contributions of electricity, today's mass market economy paradoxically offers more variety and more choices than we had in the past. And electricity continues to enable much technological innovation.



accomplished without human intervention. Virtually all progress beyond this stage has relied on electricity and electronic control devices.

During the 1930s, electrically powered mechanical devices called servomechanisms came into use. Designed with feedback capability, the new devices could automatically measure particular machine actions, identify the difference between actual and desired actions, and respond to the difference by making adjustments to achieve the actions desired. Servomechanisms were able to direct far more complex sequences of machine movements than their predecessors. But their repertoire of movements was still quite limited and had to be set in advance.

A major breakthrough came with the application of reprogrammable controls, which used automated instructions to shift machine operations in the midst of production. Initially developed during the 1940s and 1950s, reprogrammable control devices came into widespread use during the 1960s. They allowed production sequences to be altered easily in midstream in response to changes in a punched paper tape. The tape was decoded by a mechanical or optical reader attached to the machine itself.

The next step was the development of stored-program digital computers. Substituted for the cumbersome system of paper tape, the computer memory could store instructions governing every operation of an automated machine, and reprogramming was only a keystroke away. Since the mainframe computers of the 1960s were expensive, however, justifying their cost required that each one control a number of machines. Reliability came to be a problem. When a computer broke down, a number of machines were disabled, just as multiple machines had been disabled by the failure of one electric motor during the very early days of electric drive.

These problems set the stage for the microprocessor, which allowed computer control to take place at the machines themselves. Greater flexibility removed the penalty on nonstandard products and launched the trend toward customization that has since been seen in products ranging from automobiles to T-shirts. More significant, the microprocessor allowed computer-controlled machines to be linked with one another and with the various activities that support production.

Intel introduced its microprocessor, or "computer on a chip," in 1971. The microprocessor was programmable in the same way as much larger computers. Compared with the earliest mainframe, the microcomputer of the mid-1970s had more computing capacity, was 20 times faster, and cost only 1/10,000 as much. Thus began the dispersal of computers to the very sources of the information they collect and to the very processes or machines they control. This decentralized system of control, relying on a hierarchy of computers, became known as "distributed intelligence."

In the early 1980s, this new system came to the fabricating industries. In a typical configuration, several microcomputer-controlled machine tools are linked by a minicomputer, and several minicomputers are tied in turn to a mainframe. The programs for the manufacture of every part the firm makes are stored in the central database and transferred automatically from the mainframe via the minicomputers to appropriate machines in the network. In addition, information about the status of every machine, the volume of its production, and the quality of the finished parts flows back to the mainframe.

The possibilities do not stop there. An organization can link design, engineering, fabrication, production management, and even product distribution and field service through a common database. Electronic integration allows factories, and the office operations that support them, to be reorganized for maximum speed and flexibility in response to a constantly changing competitive environment.

Owing to obstacles ranging from computer incompatibility to sheer information overload, very few enterprises have yet realized the full potential of electronic integration. The pioneers of electronic integration may be acting on faith, just as many of the pioneers of electrified mechanical drive did. Computer technologies will almost certainly bring further organizational change and productivity gains to manufacturing, but it is unclear at what pace those changes will occur.

Growth falters

So far, the productivity advances accompanying the adoption of microprocessor technology in manufacturing have not been as rapid as those that occurred during the heyday of electrified unit drive in the 1920s. Poor productivity gains during the 1970s prompted skeptics to question the benefits of computerized control. Manufacturing productivity had grown at an average annual rate of 2.4% during the period 1960–1973, before the introduction of the microprocessor-based technologies. But just when the benefits of the new technologies would have been expected to begin showing up, productivity growth dropped further, to a low average annual rate of 0.2% (1973–1981). At the end of the 1970s, productivity had actually begun to shrink.

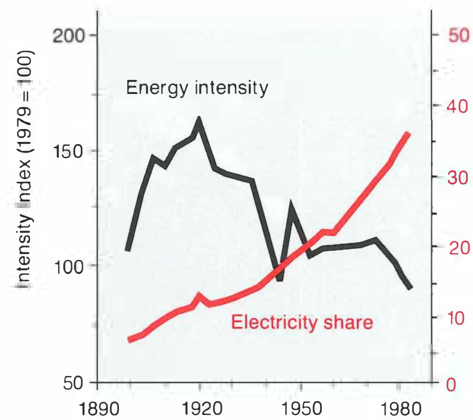
What happened? One explanation is that the emphasis during this time was on saving energy, not labor or capital. Because labor and capital are the inputs employed in multifactor productivity measurements, using more of them in order to save energy will make productivity figures plummet. Energy conservation priorities led to choices that saved energy but failed to support overall productivity growth. Other possible factors bogging down this growth were a large influx of untrained workers into the workforce and lags in the availability of new equipment.

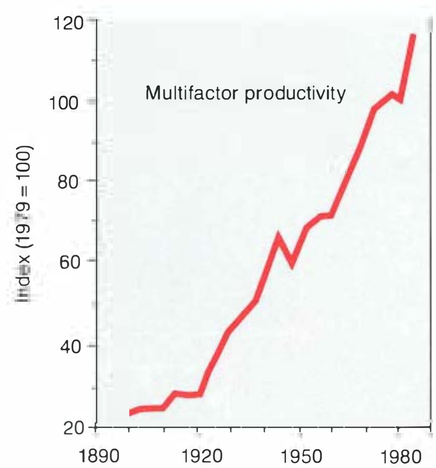
Once these conditions passed, manufacturing productivity snapped back. The period 1981–1985 saw a sharp rise in the average annual growth rate—to 4%. Recent figures confirm that the slowdown of the 1970s has indeed been reversed and that the reversal has been sustained.

Like productivity, electricity use in

Electric Power for Energy Efficiency

One hundred years of technological innovation in manufacturing, represented by steadily increasing electrification for fast, precise application of energy, has led to sharply lower energy intensity—that is, a reduction in the overall energy consumption per unit of U.S. economic output.





Electric Power for Productivity

The same period has seen sharply higher multifactor productivity, the ratio of economic output to the combined input of labor and capital. Multifactor productivity is climbing more steeply in manufacturing alone (shown here) than in the total U.S. economy, where labor-intensive service activities play a prominent role.

manufacturing has continued to grow, but much more slowly than it did in the 1920s. The average annual growth rate for 1973–1985 was only 0.3%. When electrified unit drive revolutionized industry during the 1920s, the ratio of electricity use to capital investment grew at an average annual rate of 8.3%. The 1970s saw just the opposite pattern: electricity use grew more slowly than capital investment in the period 1973–1981, resulting in a 3.5% annual rate of decline in this ratio. What's more, the electricity use–capital investment ratio remained narrowly negative in the early 1980s, even when productivity began to climb.

Do these figures mean that electricity has become less important in manufacturing? Not at all. Partly they reflect recent efforts toward energy conservation. Partly they reflect the much higher capital cost of new computerized equipment. But mostly they point to the difference between the electricity requirements of the motors that spearheaded the technological revolution of the 1920s and the minuscule requirements of today's computer technologies. The changes in the relationship between electricity and capital do not signal a slowdown in the trend toward electrification of capital, but they do point to a slowdown in the amount of electricity required to power it. Nevertheless, electricity's share of the total energy use in manufacturing, now about 40%, continues to increase, largely as a result of the growing electrification of materials processing (an important trend documented in the book by Schurr and his colleagues, but not covered in this article).

The third major trend accompanying technological progress has been declining energy intensity. Because conservation has been a national policy since the early 1970s, it is difficult to separate out the energy savings directly attributable to productivity growth and the new wave of microprocessor technology. Energy intensity declined rapidly at an average rate of 3.6% throughout the period 1973–1985, but the drop was sharpest toward the end, just as productivity began rising again. That is consistent with the historical pattern, suggesting that conservation efforts got a strong boost when the new technology, which served both conservation and overall productivity goals, came into widespread use in the early 1980s.

For the full period 1973–1985, then, all three major trends continued, but just barely. The growth in electrification and productivity was quite sluggish by historical standards and failed to keep pace with the rapid improvements in energy efficiency. So the relationship among the three trends changed. After many years of marching along together, they parted company briefly during the 1970s. When the energy shortages began to ease, however, and new technology became more widely available, lagging electricity use and productivity began to catch up, bringing the three trends once again more closely into step.

The pattern endures

The new book by Schurr and his associates links the dramatic rise in U.S. manufacturing productivity during the twentieth century to electricity-based techniques. In doing so, it addresses three interrelated questions: Why has electricity's share of total energy risen so sharply throughout this century? How has this rise been related to productivity increases? And how can it be consistent with steady improvements in the efficiency of energy use?

The answer to all three questions is the technological progress that is embodied in electrified production techniques. Two examples, one historical and one contemporary, have shown how such techniques can exert a powerful and pervasive impact on the efficiency with which all manufacturing operations are performed. To achieve this impact, both electrified machine drive and microprocessor technology have relied for their effectiveness on a unique attribute of electricity: the exceptional precision—in time, in space, and in scale—with which energy in this form can be transferred.

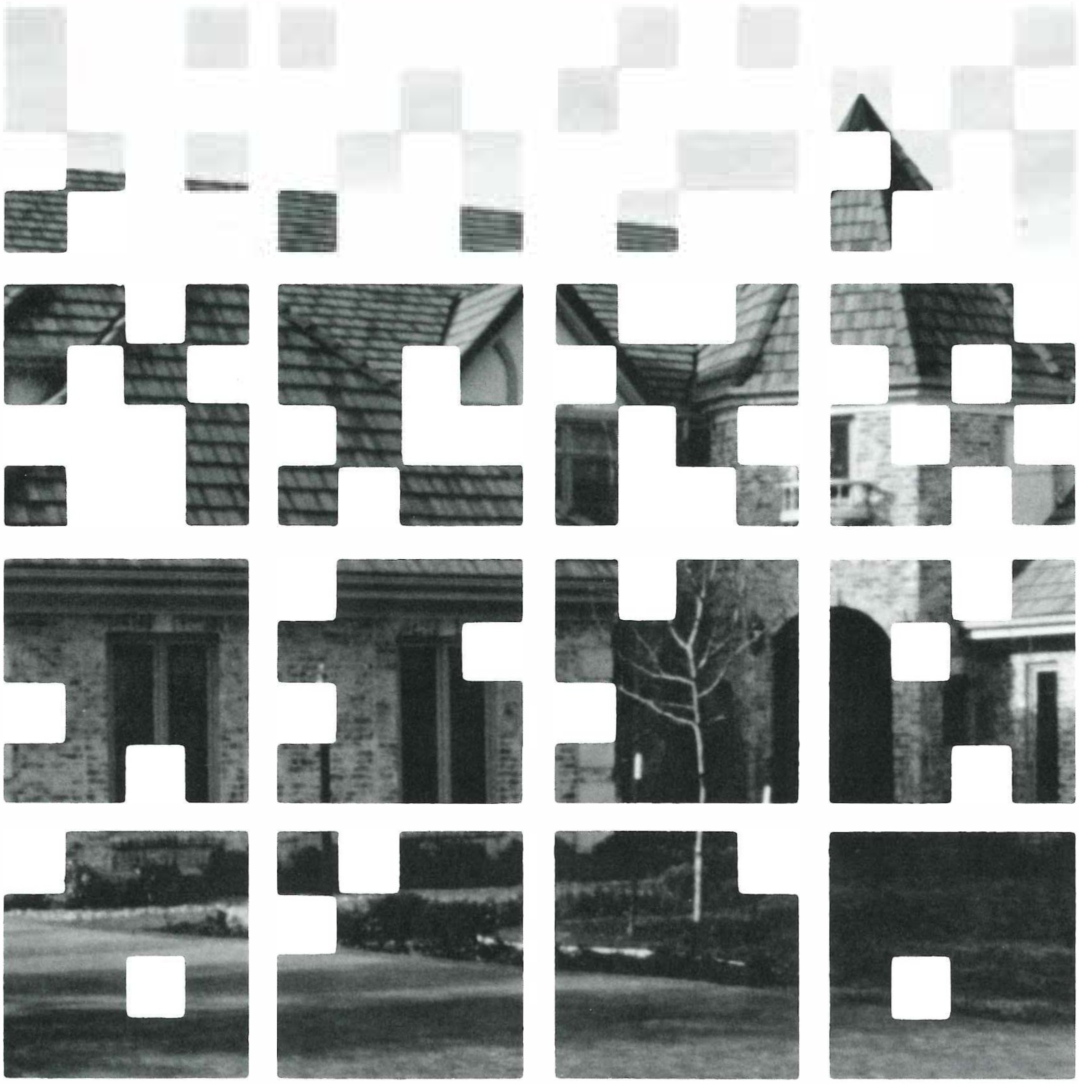
Like electrified unit drive decades earlier, today's microprocessor technology offers benefits typical of electricity-based production techniques. It provides decentralized control. It permits flexible utilization of plant and equipment as needed. It allows for easy expansion in small increments. And it allows the whole operation to be coordinated and integrated into a smoothly functioning unit. Both electric drive and microprocessor technology have permitted significant reorganization of manufacturing operations, with payoffs in both overall productivity and the efficiency of energy use. They show how electricity-based technologies can produce more output than ever before with less combined input of labor and capital per unit, and with less energy input as well.

As these advances continue, the historical rate of increase in electricity use could moderate somewhat, because the energy requirements of some of the newest computer-related technologies are minimal. Even so, dependence on electricity is likely to continue to grow. It will grow as the heavily energy-intensive materials-processing industries continue to shift from fuels to electricity and as computerized information management systems reshape the nation's productive capacity.

In short, Schurr and his associates see the productivity slump of the 1970s as an aberration and the recovery of the 1980s as a return to normalcy. The pattern is well established over the course of the twentieth century. If the 1990s conform to that pattern, electricity's share of total energy will continue to rise in concert with healthy productivity gains and continuing improvements in the efficiency of energy use. ■

This article, written by communications consultant Mary Wayne was based on *Electricity in the American Economy: Agent of Technological Progress*, a book by Sam H. Schurr, Calvin C. Burwell, Warren D. Devine, Jr., and Sidney Sonenblum that will be published in 1990.

INTEGRATED HOME AUTOMATION



Electronic intelligence for home systems and appliances is only a step away from adaptive responses and interactions that will give us far greater control, comfort, and convenience. The integrated communication channels that make these advances possible can also enhance load management efficiency and economy on both sides of the meter.

The promise of automated homes is no longer pie in the sky. We are close to the reality of household appliances and systems that "communicate"—interacting with each other and with us, not to mention with the utility, the police, and the fire department, as well as banks and brokers, airlines and travel agents, school and studio broadcasters, and any number of stores. We're seeing what market analysts call trend lines. They're profiling steady progress, and prototypes of several automated designs—including one called the Smart House, in which EPRI has a hand—are being built in several regions of the country.

We already have smart products in profusion. Microprocessor chips are as common as potato chips in American houses, bringing a measure of intelligence to TVs, VCRs, thermostats, telephones, stereos, ranges, and even coffee makers. Appliance manufacturers like General Electric and Sony are routinely incorporating programmable controls into their products.

Also on the market are smart subsystems that enable basic, if limited, automation of a few household activities. For some years now, the X-10 programmable controller has been popular for operating home lighting and small appliances, registering impressive annual sales of over 2 million units. It isn't alone; many other retrofittable designs that communicate by means of existing power wiring are available from hardware and builders' supply outlets and from such chains as Radio Shack and Sears.

Moreover, entirely automated houses are being built, featuring specialized wiring systems to accommodate all manner of present and future functions, some of which aren't even completely defined yet. The Smart House project, for instance, was founded in 1984 under the auspices of the National Association of Home Builders (NAHB), with the participation and advice of manufacturers, utilities, and trade groups all over the United States. EPRI and the Gas Research Institute are closely involved, as are a number of utilities, both gas and electric. Baltimore Gas & Electric, Columbus & Southern Ohio Electric, and Oklahoma Gas and Electric are three companies with projects under construction.

Manufacturers are coming to market with increasingly versatile electronic systems that will make intelligent homes a reality. Two examples document the point. Unity Systems (Redwood City, California) first offered its Home Manager in 1985, a combination of controller, touchscreen, and software that manages household energy distribution and use and controls security and sprinkler systems. The Home Manager can monitor up to 24 zones, control airflow (and thus temperature) in 20 of them, and execute as many as six programmed daily changes in each zone. Intended mainly for new houses, an installed Home Manager system costs from $5000 to about $20,000.

CyberLynx Computer Products (Boulder, Colorado) is primarily a software firm, but since 1985 it has produced a system called the Smarthome. Operating on radio frequencies for control signals, the system is wireless and can be owner-installed in existing homes at a cost of $1000 and up, depending on the number of sensors and modules needed. A control unit and a hand-held transmitter permit the programming of HVAC and security systems; programming changes in lighting requires the use of a personal computer.

The number of products and systems available or under development today prompts proponents of the intelligent home to estimate that by 1992 there will be 5000 such dwellings in the United States. Some even predict a 25% penetration of new home construction within the next five years.

Making the distinctions

Computer literacy certainly figures in projections for home automation. Fostered by schools and offices, it has stimulated our interest and confidence in residence-based networks where appliances—even of different types and brands communicate with each other to enhance the quality of our domestic lives.

But questions and doubts still abound, if only because "home" is such a strong image and at times resists change. Also, overlapping and competing products add their own equivocal note. Therefore, inevitable as the intelligent home is to a lot of suppliers and builders—and not a few utility executives—it sometimes seems as indefinite and remote as the often-mentioned paperless office.

Simply reeling off examples of products and systems doesn't clearly define the functional hierarchy that takes us to intelligent home environments. In fact, there are three tiers: smart products, intelligent subsystems, and integrated home automation systems.

First come smart products. These have some data processing power. Products with digital controls, for example, appeared in the 1970s. Among them are VCRs, microwave ovens, and coffee makers with digital clocks. Appliances like these rely on digital control to automate one or more functions. But at their present stage of development they can't, for the most part, exchange information with any other appliance. A microwave oven, for example, is just that; it can't accept remote time or power-level instructions or even trigger a message on the TV screen when food is ready. All it can do is beep for the benefit of people within earshot.

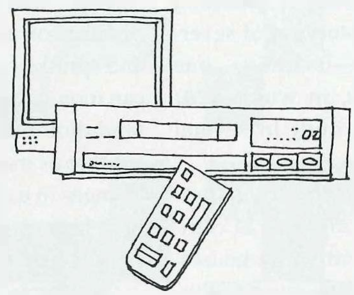
As it becomes possible to exchange information between different kinds of products, even those of different manufacturers, greater productivity in domestic management will become commonplace. This is the level of intelligent subsystems. An obvious current example is the linkage of lighting and entertainment controls with those of a swimming pool or spa. As another example, home HVAC controls could be tied in with a security system so that the programmable thermostat would lock the doors and activate the security system while turning down the heat at some designated bedtime hour.

"The distinctive feature of these intelligent combinations," says Arvo Lannus, EPRI's program manager for residential

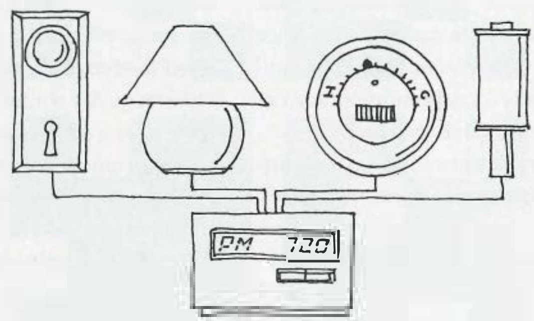
A Pyramid of Performance

What we like to call intelligence in the electronic operation of appliances is a matter of degree—from smart products to intelligent subsystems to integrated home automation systems. The progression is marked by greater interconnection for communication and control purposes. It's also marked by increasing sophistication, moving from single appliance identities to entire household functions and services.

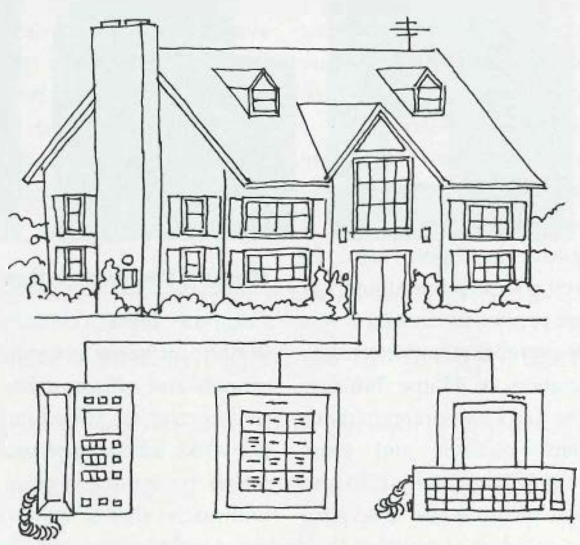
Smart Products Perhaps the most familiar smart product today is the videocassette recorder, programmable weeks in advance for repetitive or special-event TV recording. On-screen displays guide and verify the user's step-by-step commands, which can be entered on the buttons of a wireless controller from the ease of a sofa clear across the room.



Intelligent Subsystems Home security is the central feature of one representative intelligent subsystem, where several appliances are linked so that the timing and mode of operation of one controls the others as well. Given a programmed combination of hallway and outdoor lights, for example, one switch turns on all those lights at bedtime—and at the same time turns down the space heating, engages intrusion alarms, monitors all smoke alarms, and electronically locks all exterior doors to outsiders.



Integrated Automation Systems An entire home automation system interconnects everything, making it possible not only to perform more functions in concert but also to initiate or modify virtually all of them from any control point, such as a telephone (in the house or elsewhere), a hand-held VCR control, a microwave oven touchpad, a personal computer keyboard, or any of several system controllers. With the advent of smart electric meters and utility communication links, major energy-using appliances will even take advantage of low electricity rates during nonpeak hours.



customer systems, "is sensing the status of one device or appliance as the basis for controlling another. The overall service or benefit is greater than from either of them alone. The distinction is even sharper if you think of remote control—for example, using the telephone to program the microwave oven or the VCR."

One of the earliest (and now least expensive) intelligent subsystems is the X-10 line of controllers and control modules, available through Sears and Radio Shack. The controllers communicate by power line carrier, sending programmed on/off signals to other products via the modules at outlets or switches throughout the house. The most sophisticated of the X-10 controllers is programmed by personal computer but thereafter operates independently, controlling as many as 256 devices from wherever it is plugged in. A simpler X-10 controller requires no computer interface; manual programming provides control of up to eight appliances.

A key distinction in the hierarchy of product and system intelligence is response to unusual circumstances. For example, consider the idea of a digital clock with enough intelligence (and battery backup) to recognize power outages and seasonal time changes. When the rest of our household clocks become smart enough, we will no longer face the bothersome chore of correcting them manually. Instead, the master clock will respond to an outage or programmed time change and send a simple reset message to all the others—VCR, microwave, oven, alarms, and so on.

Integrated automation systems

When people talk about the intelligent or automated home, they're talking about far more than being able to program the heating system to lower temperatures when no one is home or to run the dishwasher tomorrow or both. Full home automation, the top of the pyramid, draws this definition from Arvo Lannus: "It's integrated control of all major devices and systems in the home according to the schedules and use patterns of the residents, over a cycle of weeks and months, even of seasons."

Veronika Rabl, EPRI's program manager for demand-side planning, makes a further distinction. "An intelligent home is adaptive; it takes account of changed conditions—the weather, for example, or my patterns of appliance switching and use. If I repeatedly open windows, the heating system will learn from that and reset itself to a lower temperature."

Together, their comments emphasize the notion of functions more than of appliances. Instead of telephones, TVs, and toasters, the intelligent home deals with energy, communications, security, entertainment, comfort, cooking, gardening, transportation, utilities, and so on.

Proponents of the intelligent home think and talk in terms of interaction between occupants of the home and appliances in the home—and in terms of a process rather than separate events. For home automation success, the supposition is that people will be able to communicate easily, even casually, with their integrated systems at any number of access points (called interfaces) or by means of cordless remote controllers.

Integrated home systems today typically have a microprocessor-based central control unit, applications and system software, and a variety of add-on controls for customizing installations. Examples include Unity Systems' Home Manager and Hypertek's Home Brain. Most of the systems rely on power-line-carrier signals and also use dedicated wiring for such functions as security system or HVAC control. For instance, Mastervoice's Butler in a Box uses telephone wiring, and CyberLynx's Smarthome uses radio frequencies.

But although these are all called whole-house controllers, none yet controls all major home electronic functions. At best, they integrate the functions of several selected appliances or a few subsystems. This is partly a matter of market development; people aren't fully aware of what can be done. Also, it's a matter of practicality in adapting the new systems to existing houses. "Home automation systems that offer full integration aren't yet available," acknowledges market analyst Tricia Parks of Parks Associates, who was quoted recently in *Custom Builder*. But, she contends, "they will become so as technology and expertise evolve."

Fully integrated home automation systems process information quickly: their software is able to receive several simultaneous signals from different products and systems, resolve conflicts between competing signals, prioritize needs, and make decisions. To realize this goal in the most complete manner, the NAHB Smart House is laced throughout with multifunction cable that carries low-voltage wires for telephone and data communications, coaxial cable for audio and video signals, and power wiring (*EPRI Journal*, November 1986). Any appliance from any manufacturer taking part in the Smart House development can be plugged into any outlet, and distributed logic chips—in the appliance and at key points in the core wiring—then establish the appliance identity before any current flows. Success for the Smart House hinges not only on the acceptance of its novel core wiring and control system but on the availability of a full range of compatible products.

Establishing communications standards

Today's gaps in the compatibility of smart products and systems reveal a tension born of long-standing competitive practices. Product differentiation is seen by some developers and manufacturers as a proprietary advantage and is marketed accordingly. This strategy of going it alone requires constant reevaluation as market growth speeds or slackens or as other product lines compete in breadth or capability.

Ultimately, of course, the expansion of home automation systems to accommodate more products will be a logical and necessary feature for their growing acceptance and market penetration. EPRI's research managers are convinced that the key to cost effective in-home communications networks will be their versatility in getting the most from the increasingly


JERRY KING
EASY-MATIC
EASA-PHONE
FLASH
MUTE
MUTE/MEMORY
HOLD
REDIAL
PAUSE/SAVE
PROGRAM
TV/VTR
REC MODE
CLOCK/COUNTER
CLEAR/RESET
VIDEO CASSETTE RECORDER SL-25

The Automated Home—Conversant With the Future

Communication is the key capability that will integrate today's smart products into tomorrow's fully automated systems. Heat, light, audio-video, food preparation, communications, security, and recreation facilities—all can respond to centralized controllers now, with the help of gateway devices to translate or reconcile electronic language differences. But with the eventual standardization of communications, appliances will interact automatically. New data and a location code at one point, whether from a sensor or the homeowner's direct input there, will trigger adaptive action at one or more other points.

sophisticated electronic products and appliances becoming available. The clear implication is a need for standardization in the industry.

Historically, new communications technologies develop in an environment of competing systems, free from regulation and standardization. But even as far back as the early 1920s, when competition among radio broadcasters led strong stations to jam the signals of weaker ones, the response was government regulation of what was seen to be a public resource. The allocation of specific frequencies came to be welcomed by broadcasters because it guaranteed to radio advertisers that their messages would be heard free of interference.

Such standardization usually benefits consumers in the long run; our current experience with the VHS format for home video cassettes and VCRs is an example. According to Clark Gellings, director of EPRI's Customer Systems Division, failure of the home automation industry to adopt a standard communications protocol in the very near future could seriously delay acceptance of the intelligent home. "The worst thing that could happen," he cautions, "would be a market awash in home automation products that are unable to communicate with one another."

In the current circumstances, Gellings points to the Consumer Electronics Bus (CEBus) as a timely attempt to provide standard interfaces and a common language for appliances and products from over 50 manufacturers, including Honeywell, Intel, Mitsubishi, Motorola, Sony, Texas Instruments, and Whirlpool. "The goal is for manufacturers of water heaters, electric door locks, cable TV systems, and the like to have a single set of standardized communications bridges by which signals can move from one product to another and be understood," Gellings explains.

Sponsored by the Electronic Industries Association, the CEBus is an example of open protocol, a voluntary communications standard available to all manufacturers. It's a standard with no contractual strings, no mechanism to compel compliance. The Smart House project, on the other hand, offers a proprietary communications protocol; manufacturers and suppliers negotiate agreements to incorporate the Smart House communications language into their designs. There is thus a commitment to deliver products that work in the Smart House environment.

For the time being, the emerging home automation industry is characterized by smart products that speak different languages. If a homeowner wants a thermostat to communicate with a television, an interface—an interpreter—that can translate one signal system into the language of another is necessary.

Emerging issues in home automation

Cost is a daunting issue; the range of home intelligence prices, like their capabilities, is mind-boggling. Some off-the-shelf X-10 systems retail for less than $100, but Sean Walsh, an electronics dealer in Washington, D.C., has said that fully automating a new house costs $6000 and up. Indeed, the NAHB Smart House core system (wiring and logic) is estimated to cost $10,000. Rewiring an existing house for a comparable system would cost still more. And specialized whole-house controllers, such as one from Custom Command Systems that features voice recognition, cost $40,000 and up.

Of course, home automation expense will fall as market acceptance rises. Mass production and distribution will bring prices down. However, not every system is a winner. Homeminder, a $500 low-end wireless controller jointly produced by General Electric and the security system manufacturer ADT, failed to sell and production was discontinued.

Susan Cohen, a marketing administrator at Rolm Corp., sounds a note of caution. "Just because the technology is available doesn't mean that the intelligent home will become a reality in middle America. A number of issues need to be resolved, not the least of which is the need to market a clear vision of what an automated home really is to the consuming public."

Clark Gellings sees a number of forces shaping and articulating the future of automated houses. "People want more than simply energy in their homes," he says, and he has identified what he calls the key players in making the intelligent home market a success. They include the manufacturers of entertainment products and major domestic appliances, of course. But there are also the suppliers of electric hardware, such as circuit breakers and wiring; the numerous standard- and code-setting bodies of industry, government, and the electrical trade; residential developers and builders (and remodelers); the computer industry; the designers of telecommunications networks, including local telephone companies; and banks and other institutions (stockbrokers and insurance companies, for example) that have a commercial stake in communications links to their customers' homes. Not least among these key players are electric utilities.

"We don't yet know everything that these organizations need to be doing in order to make the intelligent home market a reality," stresses Gellings. "But we do know that there is real potential for electric utilities to take a role in promoting the intelligent home to their customers."

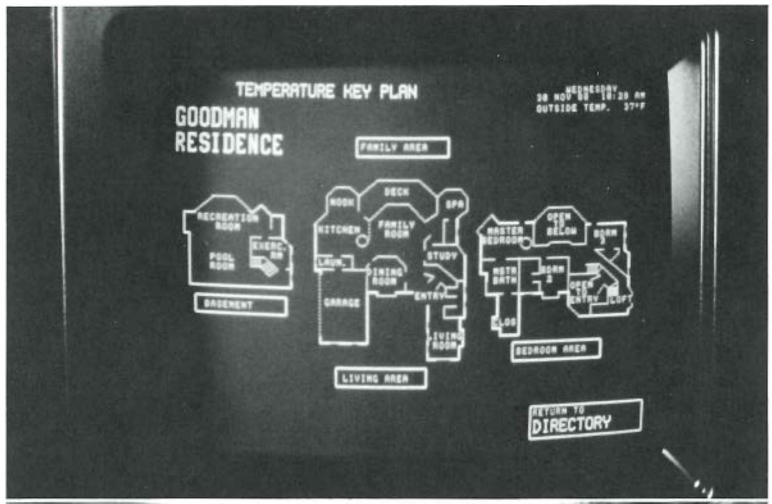
Defining utility interest

Quite apart from the traditional competition with natural gas as a household energy form, electric utilities have a special reason for taking an interest in electronic home automation. As Gellings notes, "Utilities are just now beginning to make the connection between their need to manage electricity load and the tremendous potential for doing so that is inherent in the automated-home concept."

According to Gellings, it isn't often appreciated that the intelligent home is an ideal environment in which to expand demand-side load management programs. With the permission of their customers, utilities can be fully functioning participants in automated-home communications networks, not only providing better service

Whole-House Control—Almost

Control is the objective of comprehensive home intelligence today. A representative example, the Home Manager of Unity Systems, concentrates on three major functions—space heating and cooling, security, and lighting and appliances—with principal programming and control via touchscreen. The system also accepts remote commands and reprogramming via telephone or computer. Special sensors monitor such conditions as temperature and motion (occupancy); relays and switches actuate the responses of forced-air dampers, water valves, pump motors, solenoids, lights, and appliances.



to the homeowner but enhancing their own load management objectives.

Many elaborate systems and arrangements are already in place through which utilities and their customers participate electronically in the operation of major appliances. Research under EPRI sponsorship indicates that more than 3.9 million U.S. residential appliances have some kind of communications link with electric utilities. In more specific terms, this means that about 1.5 million central air conditioners, about 360,000 space-heating systems, and more than 1.6 million water heaters can be remotely controlled by utilities. Altogether, these appliances represent about 4 GW of customer load.

But along with load management goes a need for load research. It is a vital and established practice, a necessary investment by utilities to guide their system and generation planning. Now, as the communications loops of automated houses come into being, utilities can tap into them for real-time data on their customers' appliance preferences and use patterns—invaluable for fine-tuning service costs and electricity prices.

Remote meter reading is another capability offered by an integrated electronic home, saving labor for the utility and eliminating intrusion for the customer. Both will be served by two-way communications systems and the development of what EPRI is calling the electric utility gateway.

The gateway will be a utility-owned and -installed communications device for exchanging information between the utility, the customer's meter, and the customer's automation system. Thanks to a flexible design featuring a modular interface, the gateway will be adaptable to home systems that follow the Smart House, the CEBus, or some other protocol. Its foreseen customer appeal is its ability to offer time-of-day rates and then meter money-saving responses. Utility-transmitted rate changes could even become inputs to the customer's automated program for energy services. The gateway is expected to be accessible to the utility by telephone, radio, and power line carrier—and later on by still other media. Design specifications are now being drawn up.

"Control is only one word for what utilities and householders achieve with electronic automation," points out EPRI's Veronika Rabl. "The gateway points up another word, *opportunity*—making it possible for the residential customer to operate electric appliances and systems more effectively and economically."

An example of the move toward two-way communications capability is the NetComm system, a radio repeater network being developed cooperatively by Metricom (of Campbell, California) and Southern California Edison. Installed on utility poles, the network will carry two-way communications between the utility and its customers, initially for remote reading of newly developed electronic meters. Eventually, Edison should also be able to initiate and terminate service remotely and add time-of-day rates for customer load management.

In another experimental project, Southern Bell and Georgia Power have already tested an integrated communications system that provides energy management and time-of-day pricing so that residential customers can program their appliances to take advantage of less expensive rates.

Home automation encourages customer load management simply because of the attributes of smart electric appliances and subsystems. As one EPRI researcher puts it, "Efficiency goes with intelligence in this business." The HydroTech 2000 heat pump is an example—it is 50% more efficient than conventional heat pumps and is specifically designed so that its power can be limited via utility load control signals. (See *EPRI Journal*, March 1988.) The unit incorporates an adjustable-speed drive and advanced electronics perfected through research funded jointly by EPRI and Carrier Corp. It's one of the products that will be featured in the Smart House.

But in addition to its load research and management value to utilities, home automation has a distinct future in adding value to all manner of electricity uses, most obviously through improved control and efficiency and reduced waste. The range of electricity uses and the precision of their control continue to increase, far more so than is the case with other energy forms. Electric automation is a unique means of taking advantage of those features and capabilities. Says EPRI's Lannus, "In a household setting more than anywhere else, value is a matter of perception—of convenience, comfort, speed, responsiveness." Home automation extends and multiplies these features of electricity service, he says, "because advances in electric HVAC and appliances can so easily be integrated with the sophisticated control and communications systems now coming on the scene."

Lannus, Rabl, Gellings, and their EPRI colleagues obviously are convinced. And part of their conviction comes from utility feedback, the growing realization that better load management and better customer service are both compelling arguments for electric utilities to play increasingly active, even major roles in marketing the intelligent home. ■

This article was written by John Miller and Ralph Whitaker, with background information from Veronika Rabl and Arvo Lannus, Customer Systems Division.

NDE Center

Celebrating a Decade of Achievement

EPRI's Nondestructive Evaluation Center, where research results are transformed into practical and fieldworthy tools, has racked up an impressive record of accomplishments in its first decade of operation—a performance recently celebrated by the people who made it happen.

Ten years ago, EPRI's Board of Directors gave the green light to a bold project proposal: the formation of a special facility with a mission so novel it had to be defined in terms of what it was not. The mission was not to be R&D; that was already being managed at EPRI's Palo Alto headquarters. It was not to be an applications operation; that was already being performed by vendors and utilities. The new facility was intended to occupy a position in between. It would serve as both proving ground and training camp—a place where new technologies and procedures for power plant component inspection could be evaluated and improved, and where personnel could learn to become proficient in their use.

That facility, EPRI's Nondestructive Evaluation Center in Charlotte, North Carolina, has proved to be one of the Institute's most successful and popular projects. The center's anniversary provides an opportunity to highlight a decade's worth of achievements that have saved utilities nearly half a billion dollars by turning EPRI research results into practical tools for the field.

Putting R&D to work

EPRI's research and development program has provided utilities with an array of advanced technologies, tools, and procedures to help them keep power plants operating reliably, economically, and safely. But an unproven prototype doesn't have much practical value in the field, where equipment has to perform reliably under what are often very harsh conditions. A power plant just isn't the place to debug a new piece of gear or to learn new procedures by trial and error.

Responding to the need to get newly developed inspection technologies and procedures into the field, EPRI's Board of Directors authorized the establishment of the NDE Center in 1979; the goals were to address nuclear NDE issues in an objective manner and to provide field-qualified equipment, procedures, and personnel training to the industry. J. A. Jones Applied Research, a subsidiary of the Jones Group, was selected on the basis of competitive proposals to organize, build, and operate the facility, the first of its kind in the United States.

The need for reliable, fieldworthy equipment and procedures is especially acute in nuclear power plants. Periodic in-service inspections of nuclear power plant components are required by federal law and must meet strict standards established by the Nuclear Regulatory Commission (NRC) and the American Society of Mechanical Engineers (ASME). Hidden and often subtle flaws, such as cracks that originate on the inside diameter of pipes or in welded joints, can, if left undetected, lead to forced outages to repair the affected component. Forced outages aren't cheap. In addition to paying for the repair, the utility may have to purchase replacement power, which can push the cost of an outage to nearly $1 million per day.

Like physicians examining patients for internal disorders, power plant inspectors examine components with X rays, ultrasonic sensors, and other diagnostic tools that reveal internal flaws without the need for disassembling the component or cutting into the metal. Such nondestructive evaluation is performed to ensure that components do not contain flaws. If flaws are present, their size and location must be determined to see if the component can be returned to service.

"The NDE Center tackles the issue of technology transfer," says EPRI's Gary Dau, who conceived of the center, directed its formation, and managed it for the Nuclear Power Division for the past 10 years. "The center was established to speed the transfer of EPRI research results into routine field application—to serve as a bridge between the developers and the users of the technology." Efforts to bring a newly developed technology to the field can encounter some obstacles, Dau says. "Field personnel may be reluctant to accept a new piece of NDE equipment or a new procedure for several reasons," he explains. "The technology may not be fully field-tested—there may not be enough experience under field conditions. It may require the purchase of new equipment, and utilities want proof that the capital outlay is justified. And it may require retraining personnel. The center was set up to smooth over those obstacles and reduce the risks involved in introducing new equipment to the field."

The center does this by evaluating the performance of NDE hardware, software, and procedures; by demonstrating and documenting the performance of systems; and by providing workshops and training courses to allow NDE inspectors to become proficient in the use of the equipment. In addition, the center maintains a hotline that provides utilities with rapid response to urgent problems, a service that has proved to be one of its most appreciated features and that has strengthened the rapport between center staff and plant personnel.

While all of the center's achievements can't be readily quantified, those that can be provide a quick snapshot of the facility's value to the industry. As of 1988, nearly 5000 individuals had participated in 386 training classes; there had been 121 instances of rapid response assistance to 27 different utilities for site-specific problems, usually involving a plant visit by center staff; and the center had published 106 reports dealing with real utility issues. Taken together, the center's activities have provided significant assistance to nuclear utilities, and the results of its work are being increasingly applied to nonnuclear power plants as well. EPRI has documented utility benefits in excess of $430 million on project expenditures of $28.1 million through 1988—a benefit-to-cost ratio greater than 15 to 1. In addition to this handsome return on investment, the center has provided other, less tangible benefits. According to Dau, these include serving as a focal point for objective NDE information and assistance and providing continuity to the technology transfer effort on a long-term basis.

Emphasis on realism, results

At the NDE Center, the emphasis is on solving real-world problems—with the ultimate goal of giving plant personnel the practical tools and the training they need to do their jobs better. Comprising 67,000 square feet of laboratories, fabrication and machine shops, offices, classrooms, and high-bay areas, the center is well equipped for meeting the goal.

When a newly developed piece of NDE equipment arrives at the center, the technology transfer process begins in the office area, where staff experts evaluate the system and if necessary add improvements—for example, making software menus more user-oriented. The process then moves to the laboratories, where center personnel evaluate the system on a component-by-component basis and make further adjustments until they are satisfied that the equipment is ready for field testing. But the equipment does not go into the field just yet; instead it is brought to one of the high-bay areas and put through its paces on a variety of sample flaws.

"In a normal operating environment, it's very rare to encounter flaws of any kind," says Dau. "Part of the challenge of evaluating the performance of a specific NDE system lies in having adequate samples to test it against. The cheapest approach is to take a piece of metal and make a saw cut in it to simulate a crack. But the ultrasonic reflection characteristics of that saw cut are quite different from those of an actual flaw, so it's not a realistic test." To provide the needed realism, the center has brought in retired power plant components that have actual flaws, including sections of reactor pressure vessels, piping, coolant pumps, and steam generator tubes. In addition, the staff has developed techniques to implant realistic flaws in simulated component sections. This assortment of flawed specimens housed in the high-bay areas is used to benchmark the performance of NDE equipment, as well as to give trainees hands-on experience in detecting the types of flaws they may encounter in the field.

Bridging the Gap Between R&D and Applications

Established to transform research results into practical tools and procedures for field personnel, the NDE Center provides a bridge between developers and users of advanced inspection technologies. By evaluating inspection hardware and procedures, demonstrating equipment performance, and conducting training programs, the center reduces the risks of introducing new equipment and procedures into the field.

Inspection challenges

Perhaps the most significant progress made by the center has been in improving ultrasonic testing technology and procedures for detecting cracks in the primary piping of boiling water reactor (BWR) power plants. Since the mid-1970s, intergranular stress corrosion cracking (IGSCC) in welded joints in this stainless steel piping has been of major concern to utilities operating BWRs; indeed, the IGSCC inspection challenge was one of the industry issues that prompted the idea for the center in the first place.

To locate IGSCC flaws, an inspector or an automated scanner passes a transducer back and forth across a weld. The transducer sends high-frequency sound waves into the material at a particular angle of incidence, and the reflected signals are displayed on an oscilloscope. If the waves encounter a flaw, the reflected signal changes and the operator interprets the signals to determine the flaw's size and location. Reliable ultrasonic detection of IGSCC in BWR piping is made difficult both by the nature of the cracks and by the nature of the pipe itself. The cracks are narrower than other types of cracks and usually produce lower-amplitude signals. And stainless steel has large grains that can mask or mimic subtle flaws.

Further complicating the inspection task are the weld-overlay repairs applied over cracked areas to maintain the strength of the pipe wall. These repairs involve building up the outside diameter of the pipe with a series of weld beads to a thickness sufficient to compensate for the crack. But the problem is that the overlaid material makes it more difficult to inspect what's underneath. Because of concerns about inspectability, the NRC specified that a utility could use weld-overlay repairs for no more than two fuel cycles unless NDE techniques were shown to be reliable; otherwise the piping would have to be replaced, a costly and extensive procedure that also exposes personnel to radiation.

From Prototype to Field-Qualified Hardware

Ensuring that newly developed inspection technology will perform reliably is one of the NDE Center's main missions. Center experts evaluate inspection hardware on a component-by-component basis, document its performance on realistic flaw samples, and, if necessary, add refinements until they are satisfied that the system is ready for field duty. The equipment is then taken to one of the facility's high-bay areas, where it is tested on full-sized power plant components under simulated field conditions.

In response, the NDE Center and the BWR Owners Group mounted a concerted effort to develop and demonstrate effective ultrasonic methods for monitoring IGSCC through weld overlays and inspecting the overlay material itself. This effort included the transfer to industry of several pieces of inspection hardware, including an advanced automatic ultrasonic system called Instraspect and the ALN 4000, a computer-based signal-processing system for analyzing data collected by manual and automated pipe-scanning systems. To bring BWR utilities up to speed on the new equipment and improved procedures, the NDE Center staff published reports, provided on-site assistance by rapid response teams, and developed formal training courses in IGSCC detection and sizing.

The effort paid off in a big way. The NRC accepted the new technology as effective and, instead of creating its own qualification program, now requires that BWR piping inspectors successfully complete the center's courses. Using the center-developed NDE technology and techniques has allowed several utilities to avoid costly pipe replacement. To take one example, Georgia Power estimates that applying the improved inspection techniques at its Hatch Unit 1 BWR plant helped the utility avoid $135 million in pipe replacement and purchased-power costs.

The nondestructive evaluation of heavy section components, such as reactor pressure vessels and reactor coolant pumps, presents special problems. Their size, thickness, and materials make them difficult to inspect; yet sensitive and reliable examinations are required to ensure the integrity of these critical components.

To examine heavy section components not amenable to inspection by conventional ultrasonic or radiographic methods, EPRI developed a miniature high-energy X-ray system called MINAC (Miniature Accelerator). This device has permitted, for the first time ever, inspection of the circumferential stainless steel welds in reactor coolant pumps. MINAC is lowered

Rapid Response to Urgent Problems

Fast access to NDE expertise is available through the center's rapid response hotline. Utilities in need of quick solutions to critical, short-term problems can tap center experts for objective information and assistance on NDE-related issues. Such direct assistance may involve consultation, evaluation of inspection data, a site visit by center staff, or use of the center's facilities. Rapid response activities have paid off considerably by saving man-hours and reducing or eliminating costly plant downtime.

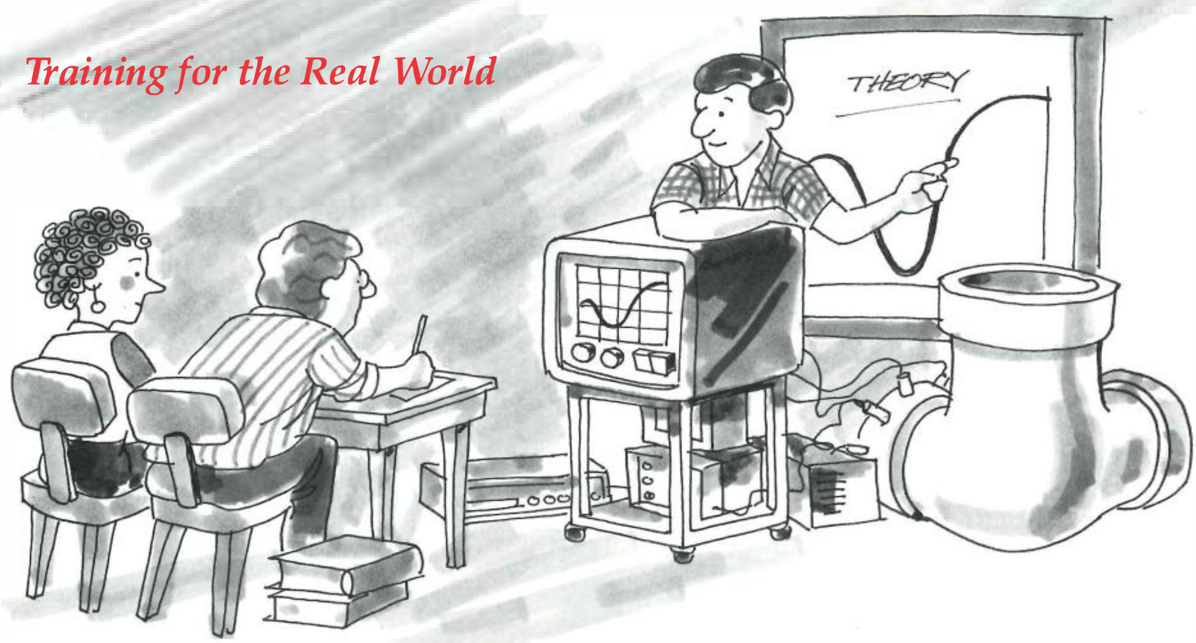
into a coolant pump by a manipulator arm, which rotates and tilts the device to aim its X-ray beam at the area of interest. "MINAC has done its job so well that the NRC has waived the requirement for reactor coolant pump inspections," says Dau. "On the basis of the favorable inspection results, the commission now allows the inspection to be postponed until the pump has to be disassembled for other reasons, representing significant savings for the utilities involved."

The NDE Center made suggestions that were incorporated into an improved version of the original MINAC design, making the system smaller and more powerful. Pacific Gas and Electric's experience with an advanced version of MINAC illustrates the system's value. During a refueling outage at Unit 1 of PG&E's Diablo Canyon plant, an inspection of the main steam reverse-flow check valve showed that a cotter pin and nut were missing from the valve disk. The NRC required the utility to verify within two weeks that the cotter pins in four similar valves in Unit 2, which was in operation, were correctly locked in position. Inspecting the first valve had been easy, since it was disassembled during the outage; but unless PG&E could inspect the Unit 2 valves while the plant was on-line, it would have no choice but to shut down the 1100-MW unit for five to seven days. Using an advanced version of MINAC called MINAC-6, which is almost 10 times as powerful as the original system, PG&E was able to conduct its inspection while the plant was on-line and verified that the valves were in good operating condition. This first application of MINAC-6 saved PG&E an estimated $2–3 million by avoiding a week-long shutdown and the purchase of replacement power. Also, the utility will be able to compare the results of the MINAC-6 inspection with subsequent inspections to detect any deterioration in the valves.

Steam turbine inspection

Catastrophic failures of steam turbine components have highlighted the need for

Training for the Real World



Practical training courses help utility personnel become proficient in the use of advanced inspection tools and techniques. The center's curriculum is designed to meet the real-world needs of the people charged with keeping their plants in good operating condition. Formal book-and-classroom instruction is supplemented with hands-on experience in detecting realistic flaws in actual power plant components.

effective NDE to detect flaws early, as well as to predict the life expectancy of components. The center's turbine program has evaluated and transferred to industry improved turbine rotor inspection systems and also a computer program for estimating remaining rotor life. Making such an estimate isn't easy; in addition to NDE, the disciplines of stress analysis, heat transfer, materials science, and fracture mechanics must be employed. In the past, rotor lifetime analyses were performed by turbine manufacturers, whose assessments about whether a rotor should be repaired, replaced, or retired tended to be overly conservative.

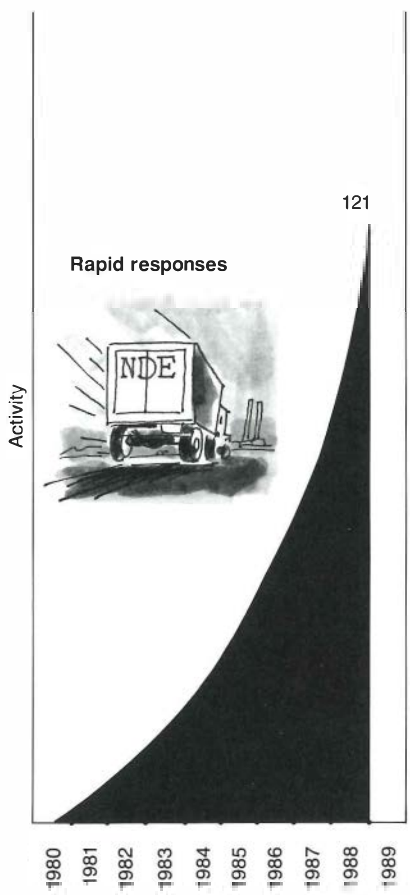
Ultrasonic examination of turbine rotors can be performed with an EPRI-developed inspection system called TREES (Turbine Rotor Examination and Evaluation System), which moves down the center of the rotor bore and extends transducer-tipped spider arms that make contact with the bore surface. Boresonic data from the scan are sent to a computerized data acquisition system, which produces a map of flaw locations and sizes. Together with material property data and projected turbine operational cycles, the boresonic data can be used with the EPRI-developed computer program SAFER (Stress and Fracture Evaluation of Rotors) to predict rotor lifetime.

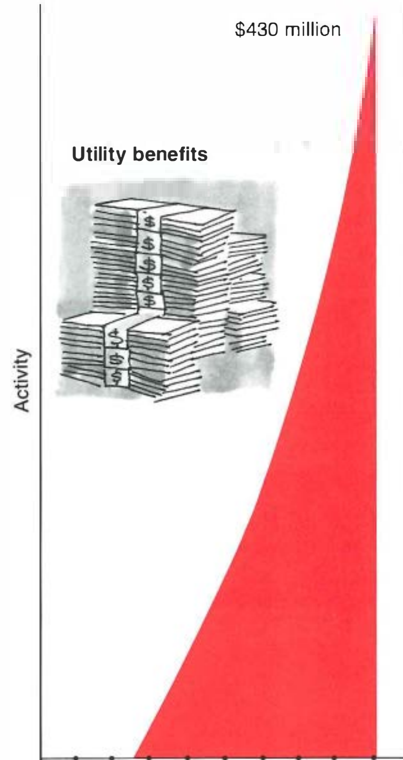
Several utilities are now using TREES and SAFER to perform their own rotor inspections and analyses, thereby reducing their dependence on the manufacturers. This capability provides a utility with a second opinion on a rotor's condition and allows it to assess any conservatism in the manufacturer's analysis. As a result, utilities can prevent both rotor failures and premature replacement. Duke Power now uses SAFER to evaluate 10 to 12 rotors a year. The code has helped the utility to avoid premature replacement of one rotor and to extend inspection intervals; Duke expects a 10-year levelized annual saving of $2.3 million.

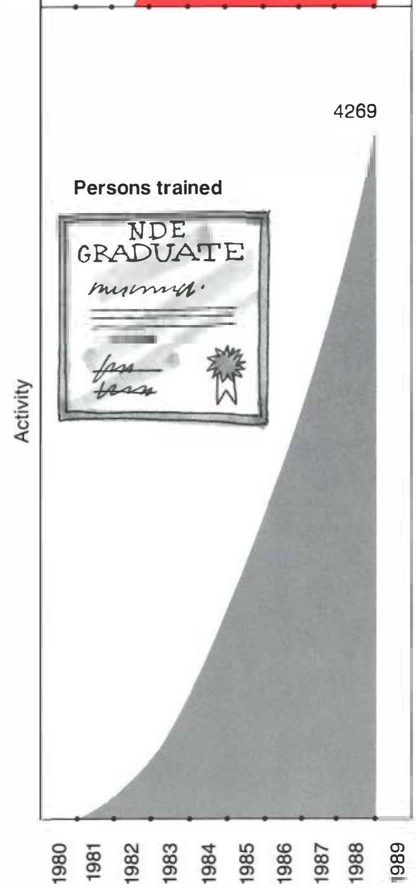
The center's turbine program is not limited to rotor bore inspections. Another turbine inspection challenge is presented by

The Measure of Success

The NDE Center's accomplishments are directly translated into benefits to member utilities in the form of financial savings and an expanded pool of NDE expertise. These benefits are ultimately passed on to customers in the form of lower-cost power and more reliable generating plants.







the region where turbine blades are attached to the turbine disk rim. The combination of high centrifugal stresses and steam corrosion can initiate cracks in the "Christmas tree" connections between the blades and the rim. Such cracks can be detected by magnetic particle testing, but this method requires removing the blades and later installing new ones. A cheaper alternative is a manual ultrasonic inspection, but this is both unreliable and difficult to perform—the complex geometry of the connections produces many extraneous signals, and the transducer must be placed precisely.

Pacific Gas and Electric was again the beneficiary of the center's work. PG&E was recently faced with the task of inspecting the blade-fit area at its Geysers geothermal power plant, where corrosion can be a problem. Recognizing the limitations of magnetic particle and manual ultrasonic inspection, the utility elected to employ a novel approach using two technologies from the NDE Center. To ensure proper placement of the ultrasonic transducer, PG&E used a new personal-computer-based beam-plotting program developed at the center. Called PC Raytrace, this sophisticated code traces the path taken by an ultrasonic beam as it passes through the area being examined and instantly displays the beam on the computer screen. In addition to allowing precise transducer setup to ensure that ultrasonic signals are sent to the area of interest, the use of Raytrace helps in the evaluation of the data. PG&E also used UDRPS (Ultrasonic Data Recording and Processing System), which captures reflected signals and displays them for analysis, revealing very subtle changes in the signals that may be caused by cracks.

By using Raytrace and UDRPS, PG&E can perform 50 examinations in the time previously required to do a single manual examination; moreover, it can perform examinations that were not possible or practical with earlier, manual methods. For PG&E, the net savings from these computer-based tools are estimated to be about $195,000 per year.

"We've seen more and more examples of utilities applying the center's work to nonnuclear power plants," says Dau. "The mandatory inspection requirements imposed by the U.S. Code of Federal Regulations for nuclear plants serve as a forcing function to improve the technology. A similar forcing function doesn't exist for nonnuclear plants. But once the improved inspection techniques for nuclear plants are available, their adaptation to nonnuclear plants is usually straightforward. It's very gratifying to see more transfer of this type."

Building on a winner

As the NDE Center approaches its second decade of operation, it will be taking on a broader mission, according to James Lang, program manager for nuclear plant operations and maintenance, who is assuming management of the center. The scope of the center's activities is being expanded to include nuclear maintenance applications projects that in the past have been separately managed by EPRI. These include the Nuclear Power Division's Monitoring and Diagnostics Center, the Service Water Assistance Program, and the Maintenance Equipment Applications Center (which is located at the NDE Center but has been funded and managed independently).

Consolidating these projects under a single program will, according to Lang, provide more efficient and streamlined management of complementary projects and will allow EPRI to take advantage of shared resources. "Integrating our nuclear maintenance applications activities into one package will let us provide utilities with a one-stop nuclear maintenance shop," says Lang. "By picking up the phone and calling one 800 number, they'll be put in touch with the person who can answer their maintenance questions—whether they involve NDE, how to fix a pump, how to repack a valve, or how to fix an electrical breaker." Lang emphasizes that the integration will not serve to dilute the NDE resources that have been the center's focus. "We have to make sure that nothing gets lost in this process of integration," he says. "We won't lose anything that the utilities have come to depend on us for. Instead we are going to offer them more. We've got a real winner in the NDE Center, and we're going to build on that."

The NDE Center has clearly played a key role in bringing the benefits of advanced inspection technology and procedures to the nuclear power industry. Moreover, the center staff has strengthened the rapport between EPRI and the end users of the technology developed by the Institute's R&D programs. Through workshops, formal training courses, and face-to-face contact with center experts during plant visits, utility field personnel have come to depend on the information the center provides and have also been able to communicate their own needs to the center staff.

"We've made a concerted effort to get our people into the field and to make contact with the people who are actually operating and maintaining plants," says Lang. Not only does the facility bridge the gap between R&D and applications, he says. "It serves as a bridge between people—and it's a two-way bridge; information flows both ways. We need to know what the field users want so we can give it to them in a form they can use. Without effective two-way communication, it's very easy to get disconnected, to lose sight of what's really needed in the field."

The need to concentrate on results that count is echoed by Gary Dau as he recalls the NDE Center's rich accomplishments over the past decade. "Getting research results into a form that is both usable and acceptable to the people in the field is a difficult task," he says, "but one that has tremendous payoffs if you can make it work." ■

This article was written by David Boutacoff, with background information from Gary Dau and James Lang, Nuclear Power Division.

TECH TRANSFER NEWS

Analyzing Cracks in Ductile Steels

Recent research in fracture mechanics—the science of structural material characteristics, stresses, and flaws that compromise integrity—makes it possible to shift from an emphasis on brittle fractures to include the realm of ductile fractures. The new focus better represents the character of pressure boundary structures in nuclear power plants, whose piping and pressure vessel materials are selected for ductility—the ability to stretch and deform. Unlike brittle fractures, which are straightforward and easy to predict, ductile fractures are complex; calculating their behavior requires the use of advanced computers.

Ten years ago, EPRI, the NRC, and others undertook research to develop basic ductile fracture methodology. Additional research extended ductile fracture mechanics to cylindrical structures, a significant development for nuclear utilities because so many plant components are cylindrical—hundreds of miles of pressure vessels, pipes, and valves, all subject to stress from the high temperatures and pressures in the nuclear primary cooling system.

Many of the piping and vessel flaw evaluation procedures derived from that effort were incorporated into ASME codes. However, the research did not cover many factors—in particular, the entire range of cylinder thickness-to-diameter ratios, crack lengths and depths, material strengths, and load combinations. Today's prescribed guidelines therefore don't consistently yield true safety margins. In fact, they often are overly conservative. Unless plant owners can demonstrate a larger margin of safety than is indicated by ASME code procedures, evidently flawed piping must be replaced, often unnecessarily or prematurely.

To meet the need for unified, extended, and updated ductile fracture mechanics formulas for cylinders, EPRI and Novetech Corp. have developed the *Ductile Fracture Handbook*. Now available is Volume 1, *Circumferential Throughwall Cracks*, the first of two volumes of formulas for evaluating the integrity of flawed cylinders in nuclear plants. It is the first consolidated source of formulas for evaluating throughwall cracks in tough ductile steels. Formula types include linear elastic stress-intensity factor, J-integral, limit load, tearing modulus, and crack-opening displacement and area. The volume also provides formulas for obtaining fracture resistance values from pipe tests.

The handbook provides the structural analyst with solutions that are easy to apply to problems involving cylindrical structures under a variety of loading conditions. Plant owners can thus demonstrate, for example, that an undetected crack would become evident by leakage long before becoming dangerously unstable.

Owners can also show where a repair based on the current ASME code would be too conservative and entail premature or unnecessary replacement. "Appendix A of ASME Section XI specifies technically adequate and safe procedures for evaluating flaws, but compliance isn't mandatory," says Joe Gilman, program manager for structural mechanics in EPRI's Nuclear Power Division. "When a utility can use another method for determining the integrity of power plant structures and justify it, this is generally acceptable."

Utilities frequently rely on outside consultants to perform flaw evaluations, which is time-consuming and expensive. The *Ductile Fracture Handbook* gives plant owners an in-house capability. "If a utility engineer is familiar with this handbook, he can do the evaluations in most cases, saving the cost and possibly the delay associated with hiring outside consultants," Gilman points out. Virginia Power, for example, recently saved $20,000 by using the handbook, he says.

An aerospace firm has expressed interest in the *Ductile Fracture Handbook*, according to Gilman. He believes that any plant or industry using pressure components can benefit from it. ■ *EPRI Contact: Joe Gilman, (415) 855-8911*

Gehl Named to FAA Committee

Sometimes technology transfer involves a kind of cross-fertilization between researchers in separate industries. For electric utilities and commercial aviation, this process may be stimulated by the recent appointment of EPRI Subprogram Manager Steve Gehl to a Federal Aviation Administration (FAA) advisory committee focusing on nondestructive inspection of older aircraft—structures, engines, and various subsystems.

Gehl's advisory appointment results from his EPRI experience in quantifying NDE and life assessment information and integrating them into power plant maintenance planning and repair/replace decisions.

According to Gehl, technology developed under EPRI sponsorship may have immediate beneficial use in meeting aviation industry inspection needs. Particularly promising for transfer is a flexible eddy-current coil device developed for inspecting turbine blades that could have application in the nondestructive examination of aircraft engines, wings, and fuselages.

The FAA committee work could be a

two-way street, according to Kurt Yeager, EPRI vice president for generation and storage R&D. "Steve's appointment will give us a window into airline inspection methods and decision processes, some of which may be translatable to utilities."

Gehl says there is a lot of ground to cover. "Nondestructive examination is a large field—not just hardware and software, but also training programs and the planning and execution of inspections and related maintenance. Utilities and the aviation industry can learn from each other in all these areas."

Metallurgy is the foundation of Gehl's work at EPRI—three years with materials problems that affect fossil power plant performance and availability and four earlier years on nuclear fuel rod performance. Gehl joined the Institute in 1982 after seven years at Argonne National Laboratory. ■ *EPRI Contact: Steve Gehl, (415) 855-2770*

Coal Quality Center Goes Commercial

EPRI's Coal Quality Development Center is changing its status. As of January 1, 1990, it will become part of CQ Inc., EPRI's first subsidiary, ready to work for utilities, government agencies, and others in a profit-making mode. CQ Inc. will maintain the CQDC research and development program for EPRI, DOE, and state agencies; but it also will independently assist utilities with coal-purchasing decisions; test new coal-cleaning, -blending, and -handling equipment for manufacturers; and solve coal-cleaning-plant design and operating problems for coal companies.

The new organization enables EPRI to continue R&D and demonstrations even though its financial commitment will continue to taper off from the level of a few years ago. The Institute will own all CQ Inc. stock but will transfer ownership of the facility, and will license several R&D products, to the new subsidiary. Costs for routine maintenance, overhead, and improvements will be paid proportionally by CQ Inc. customers.

Utilities, coal companies, and manufacturers of coal-cleaning equipment will have direct access to CQ Inc.'s staff and facilities. The subsidiary will be able to perform proprietary research for its customers (EPRI's nonprofit status has precluded this), but the results of EPRI work will be publicly available. Unlike EPRI, CQ Inc. will be a government contractor, working directly for DOE and state agencies. "This should result in a greater overall investment in R&D that directly benefits utilities," says Clark Harrison, longtime EPRI project manager at the center.

EPRI will continue to fund several projects, with CQ Inc. as the contractor. The ongoing work includes a DOE-cofunded demonstration of advanced coal-cleaning technologies, investigations of trace elements in coal and methods for removing them, and development of a coal quality expert system. EPRI will also continue its cosponsorship (with six utilities) of a project on coal handleability—that is, how well coal moves through power plant equipment. ■ *EPRI Contact: Clark Harrison, (412) 479-3505*

Expert System Guides Emergency Procedures

A critical aspect of nuclear plant safety is what control room operators do to prevent transient events from developing into serious accidents. Operators must interpret the state of a plant and respond to any upset in a context of prescribed emergency procedures that are very complex. To aid their efforts and reduce the chances of error, EPRI developed the Emergency Operating Procedure Tracking System (EOPTS) and demonstrated its worth at Taiwan Power Co.'s Kuosheng BWR training facility.

Results from that testing show that EOPTS has a marked effect on the performance of control room crews. Crews using the system displayed greater consistency, experienced fewer discrepancies, and achieved greater success in recovering from discrepancies when they did occur—improvements that culminated in a 60–75% reduction in response time.

The computerized system monitors plant performance and status factors that are essential to symptom-based emergency procedures. Then, in an emergency, it coordinates all available data with high-level cues that show operators which portions of the emergency procedures are applicable—thereby enhancing operator ability to interpret and apply procedures and, ultimately, reducing human error and increasing safety.

EOPTS takes the form of a compact, fast-running software module that uses expert systems technology to integrate a safety parameter display system with emergency operating procedures developed by the Boiling Water Reactor Owners Group. The system was installed and evaluated with human factors techniques for six accident scenarios: anticipated transient without scram (ATWS), radiation release accident due to steam line break, loss of emergency core-cooling system, loss of reactor pressure vessel level indication, loss-of-coolant accident with drywell/primary containment hydrogen control, and ATWS with abnormal suppression pool level.

Taiwan Power is using EOPTS for operator training. U.S. utilities can obtain the system from General Electric. ■ *EPRI Contact: Bill Sun, (415) 855-2119*

Environmental and Health Assessment

TOXRISK Update

by Abe Silvers, Environment Division

Utility companies may use and produce chemicals whose effect on human health must be evaluated. The risk to human health from exposure to a potentially toxic chemical is determined by two equally important factors: the level of human exposure and the potency of the chemical for causing a health effect. To ensure a safe occupational setting and to protect the public and the environment, utility risk managers assess both of these factors for the chemicals of concern.

The risk from chemical exposure decreases with exposure level and becomes vanishingly small at very low levels. This concept of the dose-response relationship is fundamental to toxicology. It implies that human health can be adequately protected by controlling exposure to a toxic chemical.

When assessing risk from exposure to potentially cancer-causing chemicals, the Environmental Protection Agency and other regulatory bodies often make the health-protective assumption that any exposure, no matter how small, entails some risk. This assumption leads to the calculation of what are called plausible upper limits to human risk by applying statistical dose-response procedures to laboratory animal data. Often, animal results involving laboratory exposures many times higher than that of any human population must be used in making these calculations because human data suitable for risk estimation are not available and because the use of lower exposure levels may not allow the detection of response in even a large laboratory study group. To enable utilities to consider these animal data, EPRI sponsored the development of TOXRISK (RP2310-2), a software package that facilitates risk assessment.

ABSTRACT *EPRI developed the computer program TOXRISK to help utilities assess the potential health effects of chemicals they use and produce. A new version will soon be released that includes models capable of estimating risk as a function of time to exposure as well as level of exposure. Other enhancements to the program include improved graphics capability and increased user-friendliness.*

TOXRISK features

Risk assessment methods predict the probability of a toxic effect from exposure to a chemical substance. A group of animals, usually rats or mice, is exposed to a particular material at various doses; the subjects are then evaluated at the time of death (natural or induced) to determine if they developed cancer or some other disease. If cancer is of primary interest, the number of autopsied animals with tumors is divided by the number of animals in a dose group to yield the proportional rate of response to the dose. With this dose-response information, two extrapolations are performed. The dose-response relationship is extrapolated to a low-dose region to estimate a safe dose at an acceptable risk of one extra cancer in a large population (conventionally taken to be between 10,000 and 1,000,000 exposed individuals). A statistical model is fit to the data and is used to calculate the extra risk of cancer for a small incremental exposure. The corresponding dose is also extrapolated to a dose for humans.

The basic function of TOXRISK is to construct dose-response relationships for health effects, generally cancer, from animal data. The user can supply estimates of exposure to obtain overall estimates of excess risk (the extra probability of health effects occurring as a result of exposure). Alternatively, the user can use the estimated dose-response relationship to predict exposure levels consistent with predetermined levels of excess risk (e.g., 1 in 1,000,000). In either case, the user selects the method for making the animal-to-human conversion.

TOXRISK facilitates the input and management of toxicological data and automatically makes statistical and mathematical calculations. It performs standard statistical tests on the data to determine dose-related effects. The software's data management capabilities ensure that the appropriate mathematical and statistical procedures are being applied. Its improved computer algorithms permit calculations to be performed interactively in most cases.

To allow the assessment of risk under a range of alternative assumptions, TOXRISK fits several mathematical dose-response models to the toxicological data and calculates related statistical parameters. One of these models is the linearized multistage model, which is widely used by regulatory agencies. The user can be confident that the implementation of this model is consistent with regulatory practice, since the developers of TOXRISK also developed the programs used by the regulatory agencies. Other models covered by TOXRISK are *K*-stage models (for *K* from one to six), the Weibull model, the log-normal model, and the Mantel-Bryan model. TOXRISK can produce graphs to show how the models fit the toxicological data.

A batch feature allows a large number of risk assessment approaches to be applied automatically to different sets of toxicological data. TOXRISK provides a summary of the calculations performed on a group of data sets. It can output results to a computer screen, a printer, or a computer file.

Data entry is internally quality-controlled. Since the data are validated as they are entered, many common data entry mistakes are eliminated. Moreover, TOXRISK makes it easy to store and modify such animal and human parameters as body weight, breathing rate, and life span and to apply them correctly in risk calculations. It can also supply default values for these parameters.

TOXRISK employs several user-friendly tools, including pull-down windows and on-screen help. Also, the user can switch temporarily to a DOS shell to perform other DOS applications without permanently exiting TOXRISK.

With all these features, Version 1 of TOXRISK has enabled utility managers to perform risk assessments efficiently on IBM-compatible personal computers. Risk assessment concepts are constantly changing, however, as more sophisticated biological studies are performed. Therefore, Version 2 of the program is to be released this winter. As well as enabling more complex assessments, it offers improved user-friendliness and graphics capability.

Time-to-tumor studies

Toxicologists have designed studies to determine the time after initial exposure at which a tumor seems to occur. Animals are sacrificed at specified times (serial sacrifice) if a tumor is not directly observable and are autopsied to determine if a tumor is present. These studies are called time-to-tumor studies.

The data provided by this kind of study are extensive, and their evaluation requires more sophisticated models than the models in Version 1 of TOXRISK. These more complex models can be viewed as producing dose-response curves that are also a function of time. If the time considered is a lifetime, then the usual risk assessment can be performed with the models. For example, Figure 1 presents data on the time and cause of death for rats that have been given toxic food. This information provides a dose-response curve, which is then used to predict risk to humans (Figure 2).

Some of the most frequently used time-to-tumor models have been added to TOXRISK, along with capabilities for creating and managing time-to-tumor data sets. These models enable the risk manager to calculate risk-related

Figure 1 This TOXRISK screen shows an example of data for a time-to-tumor model in which some animals die from a tumor (F) and other animals die from competing causes (C). The time to death is expressed in weeks from the time the tumors were observed.

INCIDENCE DATA, GROUP 2 of 3

DATASET NAME: C:\TOXVER2\TEST.TXS\TIME1

TITLE: Test for time-to-tumor models
ROUTE/DOSE UNITS: FOOD (mg/kg/day)   SPECIES: RAT

TIME (weeks)	# OF ANIMALS	TUMOR CONTEXT	TIME (weeks)	# OF ANIMALS	TUMOR CONTEXT	TIME (weeks)	# OF ANIMALS	TUMOR CONTEXT
9	1	C	35	1	F	45	2	F
15	15	C	36	1	F	47	1	F
15	3	F	38	2	F	49	8	C
24	1	F	39	2	F			
26	1	C	40	1	F			
30	1	F	41	4	F			
31	1	F	42	1	F			
34	1	F	44	3	F			

TEST FOR TIME-TO-TUMOR MODELS

Dataset: C:\TOXVER2\TEST.TXS\TIME1

		Exposure Pattern	
Model:	One Stage Weib	Age Begins: 0	Age Ends: 70
Target Species:	Human	Weeks/Year: 52	Days/Week: 7
Route:	Food 100%	Hours/Day: 24	

Animal to human conversion method: MG/KG BODY WEIGHT/DAY

Unit Potency [per mg/kg/day] (computed for Risk of 1.0E-6)
MLE = 4.7933E-002   Upper Bound (q1*) = 6.5663E+001

Dose Estimates (ppb)

Extra Risk	Time	95% Lower Bound	MLE
1.0000E-006	70.00	7.6147E-004	1.0431E+000
1.0000E-005	70.00	7.6147E-003	1.0431E+001
0.0001	70.00	7.6151E-002	1.0432E+002

Figure 2 This TOXRISK screen presents human risk estimates derived from sample animal data by using a linearized model. The potency of the chemical in question has been calculated, as well as dose estimates corresponding to extra risks of 10^{-6} to 10^{-4} (i.e., one extra cancer in a population of 1,000,000 exposed individuals to one extra cancer in a population of 10,000). For each category of extra risk, the 95% lower bound of the dose and the maximum likelihood dose estimate (MLE) are given.

doses that are dependent on the period of exposure as well as on a specific exposure level. Such factors as the time from the appearance of a tumor cell to the resulting tumor response can also be calculated.

One of the time-to-tumor models included in Version 2 of TOXRISK is the Armitage-Doll model, which allows the user to vary the experimental exposure level in the extrapolation process. In the course of an experimental study, for example, the toxicologists may revise the exposure protocol to prevent severe damage to the animals or their early death, or to represent more realistically the actual exposure pattern that people experience. TOXRISK can now derive risk estimates from such data.

Another of the time-to-tumor models available in TOXRISK Version 2 is a biologically based model that can be used to show how a chemical exposure affects the net growth of both precancerous and cancer cells. This model is a form of the Moolgavkar model based on an expression by Thorslund.

Other enhancements

The graphing procedures of TOXRISK Version 2 are internal (unlike those of Version 1, which depend on Lotus graphics) and are much faster and easier to use. Also new is the ability to graph lower bounds on doses associated with risk to a target species and computed by using dose-response models. The menus have been streamlined with many windows, and maximum RAM requirements have been reduced by more than 50K.

Version 3 of TOXRISK, expected to be released next spring, will include graphing of the time-to-tumor models. This new version will contain data for selected chemicals from the National Toxicology Program CBDS (Carcinogenesis Bioassay Data System), a database that includes many of the lifetime studies on animals for a large series of substances. Also available will be a system for selecting studies from this database to create a TOXRISK data set. The utility manager will then have the ability, with very user-friendly software screens, to choose a substance and evaluate the cancer risk for a variety of data sets. Also planned is extensive help (including a tutorial) on the use of risk assessment.

Demand-Side Planning

Measuring Direct-Load-Control Impacts

by Steven Braithwait, Customer Systems Division

ABSTRACT *In order to evaluate the cost-effectiveness of demand-side management programs, utilities need reliable estimates of the programs' load and energy impacts. EPRI has recently developed the duty-cycle approach, a method for evaluating and predicting the impact of one of the most common types of load management program, residential direct load control. The duty-cycle approach, based on the analysis of load data from metered appliances, has been applied to direct-load-control program data from three utilities.*

Direct-load-control (DLC) programs have been adopted by a large number of utilities. A 1988 EPRI survey of residential demand-side management projects identified over 360 utilities with active load management programs designed to cycle, or shed, the load of various residential appliances through direct utility control. These utilities reported almost 1.5 million points of control for air conditioners and close to 1.7 million points for water heaters. In addition, a number of other utilities are now assessing or testing new DLC programs. Reliable estimates of the load and energy impacts of these programs are crucial to optimal program design and to the evaluation of the programs' cost-effectiveness.

The duty-cycle approach

The duty-cycle approach combines an engineering-based approach that accounts for the way appliances operate under natural and utility-controlled conditions with an empirically based statistical approach that accounts for the effects of consumer behavior. This combined approach can be used both to measure the impact of an implemented load-control program and to simulate, or predict, the impact of alternative DLC strategies. The approach has been applied to DLC program data in three utility case studies.

Duty cycle is a convenient means of representing energy use based on the standard kilowatthour measure. The average duty cycle of an appliance is the percentage of time that the appliance is used during a measurement period. An air conditioner with an estimated connected load of 4 kW and measured energy use over a particular half-hour period of 1 kWh, for example, has an average duty cycle of 50% for that half-hour period (1 kWh/0.5 hour/4 kW).

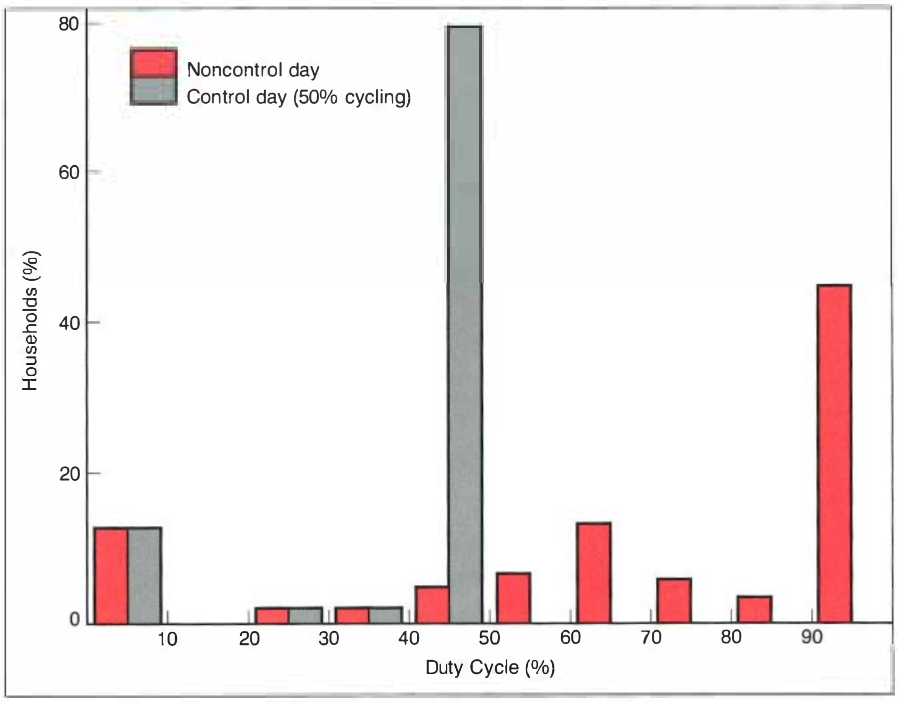
The duty-cycle representation of energy use is well suited to DLC program analysis because DLC programs achieve load and energy reductions by altering the natural, or uncontrolled, duty cycles of appliances. Implementation of a cycling, or shedding, strategy affects an appliance's duty cycle by limiting its operation and scheduling it during the control period.

A given cycling strategy, however—such as one that cycles air conditioners off for 15 minutes every half hour—will reduce energy use only for those appliances whose natural duty cycles exceed the upper limit imposed by the strategy—in this case, 50% (15 minutes/30 minutes). In addition, the impact on appliances with natural duty cycles that do exceed the limit varies with the difference between the natural duty cycle and the upper limit.

Because the impact of cycling is not the same across appliances, the duty-cycle approach focuses on the distribution of duty cycles across the population of appliances, rather than on the simple population average. The duty-cycle distribution of a population of appliances is a frequency distribution of individual appliance duty cycles for a specified time interval.

Shown in Figure 1, for example, is an actual uncontrolled duty-cycle distribution for Athens, Tennessee, air conditioners for a particular half-hour period, as well as the duty-cycle distribution that would be expected to occur if 50% cycling were imposed (i.e., if the air conditioners were turned off for 15 minutes each half hour). With cycling, all the air conditioners that would normally have duty cycles larger than 50% would be constrained to duty cycles of 50%. But the use of air conditioners with natural duty cycles below 50% would be the same for control and noncontrol days because this part of the duty-cycle distribution is not affected by cycling.

Figure 1 Frequency distributions of air conditioner duty cycles for a half-hour period on a hot summer afternoon. A wide range of natural duty cycles is shown on days of no load control, with a relatively high proportion of air conditioners operating near full capacity (90–100% duty cycle). On controlled days, a 50% cycling strategy (air conditioners cycled off for half of each half-hour period) is expected to create a constrained distribution of duty cycles. The bars represent the percentage of households whose air conditioner duty cycles fall within each 10-percentage-point range.



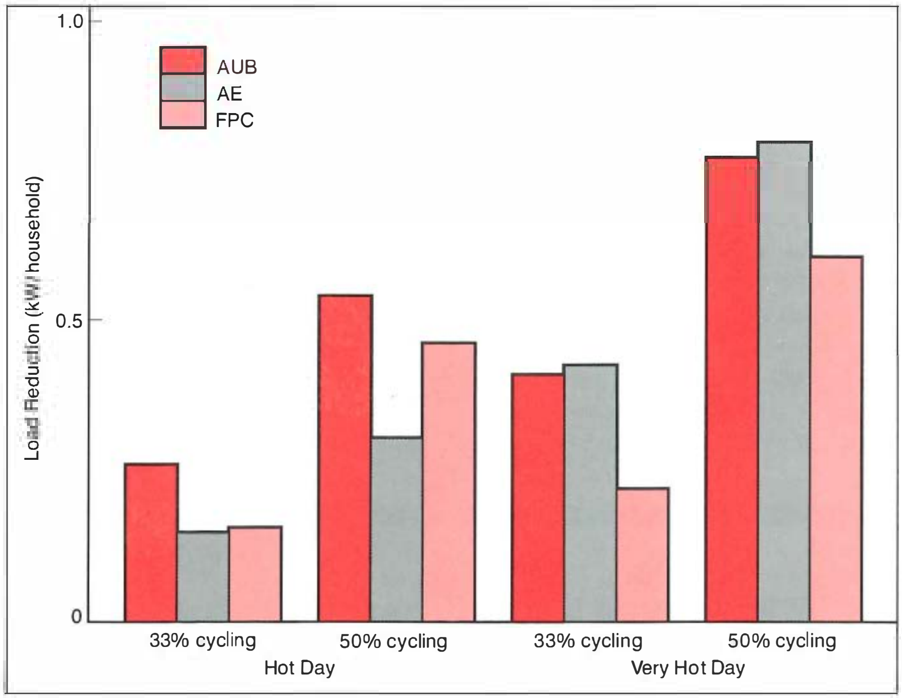
Estimation of appliance load impacts

Estimating the impact of a DLC program is difficult because the actual load that would have occurred in the absence of control is never observed. One standard approach to estimating the load impact of a particular control action is to calculate the difference between the curtailed load on the day of control and the uncontrolled load on a comparison day, typically characterized by similar weather conditions. This comparison day approach often uses aggregated load data at the system, or perhaps substation, level because data at the appliance level are usually not available. Finding days with truly comparable weather conditions is also difficult. Moreover, such approaches do not provide the capability to estimate the impact that would be likely to occur under conditions different from those actually observed.

Given the appliance-level data collected in the three case-study utility programs examined in this project, the calculation of load-control impact, facilitated by the use of the duty-cycle approach, can be accomplished in a number of ways. The most straightforward approach uses the empirical duty-cycle distribution that is calculated for particular days to simulate the likely impact of a given cycling strategy. This approach requires information on only uncontrolled days in order to simulate the impact of alternative cycling strategies.

The load impact of a strategy is calculated by accounting for the different relative frequencies associated with each duty-cycle range on a control day and on a noncontrol day. In Figure 1, for example, approximately 45% of the appliances in the sample have natural duty cycles between 90% and 100%. For each

Figure 2 Shown are average estimated load reductions per household from air conditioner cycling at Athens Utilities, Atlantic Electric, and Florida Power. Load reductions, as expected, are greater on hotter days and for more severe cycling strategies.



range of duty cycles, the implied duty-cycle reduction derived from the cycling strategy and the relative frequency of that range is computed. By combining this information across ranges, it is possible to compute the average duty-cycle reduction for the whole sample. In the last step of the procedure, the duty-cycle impact is converted to a load impact by multiplying by the average connected load. This procedure can be used to approximate the load impact of any cycling strategy.

Figure 2 presents estimates of average air-conditioner load reductions calculated by this approach using data provided by the three case-study utilities—the Athens (Tennessee) Utilities Board (AUB), Atlantic Electric Co. (AE), and Florida Power Corp. (FPC). Load impacts are presented by day type and cycling strategy for the critical late afternoon period (5:30–6:00 p.m. for AUB, 6:00–6:30 p.m. for AE, and 5:00–5:30 p.m. for FPC). For each of the two temperature-based day types considered, average load reductions resulting from 33% and 50% cycling are reported. (For AUB and AE, the 50% cycling refers to 15 minutes cycled out of 30 minutes, while for FPC the cycling duration was actually 16.5 minutes, or 55%.) The fact that the day-type definitions differ, particularly for the hot days, is part of the reason for the differences in estimated load reduction; however, the estimated reductions are quite similar for the very hot day type, which represents approximately the hottest 15–20% of summer days in each case. Also, the FPC results should be considered preliminary, not having been fully compared with previous utility assessments.

The average load reductions shown in Figure 2 depend upon a number of factors, only some of which have been explored to date. The amount of load reduction contributed by various households and the number of households falling into each group (Figure 1) are of particular interest. At FPC, for example, the estimated load reduction for a 55% cycling strategy on the very hot day ranges from 0.4 kW (for households with natural duty cycles between 50% and 60%) to 2.1 kW (for those with natural duty cycles greater than 90%). The average load reduction for the households affected by the cycling strategy (those with natural duty cycles greater than 45%) was 1.2 kW. Thus, the overall average load reduction of 0.6 kW (Figure 2) reflects the fact that a number of households' air conditioners are cycling at rates lower than 45%, even on very hot days, and are unaffected by cycling.

Impact-prediction model

The ultimate goal of the duty-cycle research is the development of an empirically based, transferable model of DLC program impacts that can simulate potential load impacts under a wide range of cycling strategies, weather conditions, and household characteristics. This model, called the impact-prediction model (IPM), will allow utilities considering DLC programs to predict the probable impacts of various control strategies by using local weather and customer data without having to collect end-use data or conduct a DLC test program. An initial application has resulted in the successful development of a weather-based impact-prediction model, which is described below.

The first step in the development of the weather-based IPM was to represent duty-cycle distribution by a parameter-based distribution function. The parameters were then related to weather conditions. The beta-density function was selected to develop parameters for the duty-cycle distribution because of its flexibility and general conformance to typical duty-cycle distributions. The final step in the development of a transferable model will be to explain the two parameters of the beta distribution (the mean and variance) in terms of local weather conditions and customers' observable demographic variables.

To date, local weather variables have been successfully correlated with the beta-distribution parameters in the AUB and FPC cases. The weather-based impact-prediction model has shown itself to be an effective predictor both of duty-cycle distribution and of load impact. The analyst supplies only the appropriate weather conditions, time of day, and average air conditioner capacity in order to estimate the impact of any desired cycling strategy on air conditioner load.

The load reductions predicted by the weather-based IPM closely track those calculated from the empirical duty-cycle distributions. Each of the impacts estimated by the duty-cycle approach is well within the 95% confidence interval of the IPM's impacts.

Ongoing research includes analysis and validation of the weather-based IPM for Atlantic Electric and Florida Power. Further effort is needed to expand the methodology to include customer and dwelling characteristics in order to account for differences among utility customers, and to address other issues such as the possible increase in load, or payback, following release of control.

EPRI perspective

This research complements some previous EPRI work: periodic surveys of utility demand-side management programs (CU-6546), which include utility-reported estimates of average DLC impacts; an attempt to develop transferable relationships between reported load impacts and differences between utilities (EM-4588 and EM-3861); and LOADSIM, a building-simulation model that permits calculation of potential load-control impacts on the basis of engineering principles (EM-3249). The empirically based analysis of highly disaggregated, individually metered appliances will provide a useful set of tools for utilities interested in measuring the impact of current programs or assessing the likely impact of a wide variety of potential programs.

Market Assessment

Planning and Forecasting Under Uncertainty

by Peter Cleary and Ray Squitieri, Customer Systems Division

ABSTRACT *Although models used in planning and forecasting have become increasingly large and complex, their point-estimate forecasts reflect only one possible future scenario. Planners and forecasters need a means of dealing with uncertainty. A recent EPRI scoping study has combined the Market Assessment Program's experience in developing powerful models to forecast electricity demand with the Utility Planning Methods Center's efforts in applying a variety of probabilistic and scenario methods to uncertainties in supply-side issues.*

Utility managers want analytical tools that are accurate, easy to use, and useful in making decisions. Unfortunately, what they get sometimes fails to meet these standards. The computer modeling community long believed that bigger, more complex models were the road to better planning. More time, more equations, and more money, it seemed, would make the new models so accurate that they would supplant older methods.

But large macroeconomic models failed entirely to anticipate major changes in an increasingly turbulent external environment. Moreover, forecasting comparisons often conclude that complex methods perform no better than simple methods. Complexity and detail do not always, it seems, lead to greater accuracy. Complexity also tends to make a model difficult to use and, more important, difficult for decision makers to understand.

Deterministic, single-outcome forecasts appear to be less relevant in today's world of rapid and unexpected changes. Utility decision makers now recognize the value of developing flexible plans on the basis of a range of outcomes rather than fine-tuning a single forecast.

Utility planners also recognize that accuracy is not the only criterion for judging forecasts. In particular, as utilities have expanded their planning to incorporate a wide range of demand-side management (DSM), marketing, and rate design options, they have recognized the value of detailed end-use forecasting and planning models, such as REEPS, COMMEND, INDEPTH, and HELM. EPRI has responded by moving toward more user-friendly, PC-oriented tools that provide the details needed to develop integrated resource plans.

To better address the issues of uncertainty, in 1988 the Customer Systems Division began a project designed to help utilities treat uncertainty, communicate the results, and incorporate them into the making of decisions. A scoping study jointly funded by the division's Market Assessment Program and by EPRI's Utility

Table 1
PHASE 2 OBJECTIVES AND POSSIBLE TASKS

Objective	Proposed Task
Simple screening tools with probabilistic component	Develop simple spreadsheet models with simulation software
Links to decisions	Add decision capability to end-use models
	Conduct probabilistic approach case study
Scenario approach tailored to utilities	Conduct scenario case studies
Transfer of scenarios	Conduct scenario workshops
	Prepare guidelines on scenarios
Transfer of probabilistic and statistical approaches	Prepare guidelines and conduct workshops

Planning Methods Center set out to combine the UPMC's experience with uncertainty in capacity planning and fuel contracts with Market Assessment's experience in marketing, forecasting, and demand-side planning.

The scoping study team of Applied Decision Analysis and Barakat, Howard, and Chamberlin identified three major approaches to addressing uncertainty: scenario, probabilistic, and statistical.

Comparison of methods

The *scenario* approach focuses on major changes in the external environment. Scenarios are qualitative, internally consistent descriptions of plausible states of the world. Scenario results are most commonly presented in the form of stories. The company best known for its scenario work is Royal Dutch Shell. Utilities known for scenario work include Southern California Edison and Georgia Power.

The scenario approach deals well with planning and forecasting problems that involve possible shifts in the external environment. Scenarios can combine many complex uncertainties to produce independent but internally consistent views of the future. Consequently, this approach suits questions in which uncertainties are numerous and interrelated. It can provide qualitative insights about key uncertainties. Scenarios have been particularly effective for communicating results to decision makers. In general, however, they provide no quantitative means of evaluating different strategies; this often results in different strategies corresponding to different future views of the world. Managers accustomed to quantitative analysis may be uncomfortable with the storylike structure of scenario analysis.

The *probabilistic* approach uses techniques of decision analysis to produce quantitative measures of possible outcomes. Results are most often presented through such measures of probability as the cumulative distribution function; the analysis generally uses a computer model to determine the consequences of major uncertainties.

This approach works well for short-term or end-use analyses. In these cases, the analyst can identify key factors affecting the problem and determine their possible values and probabilities. The probabilistic approach may also work for longer-term problems and for questions of marketing, planning, and corporate strategy. It works best when the analysis can be tied directly to a decision. Because it provides explicit likelihoods for a range of possible results, the probabilistic approach makes it easy to compare different decisions. It does not work well when the intended audience is not comfortable with quantitative analysis.

The *statistical* approach uses quantitative techniques from statistics and econometrics. Results often appear in the form of variances and confidence intervals around a forecast. This approach deals well with short-term, random fluctuations, such as weather. It focuses on uncertainty in the forecasting model parameters, which rely on historical data and do not take into account shifts in the future utility environment. As a result, the statistical approach fares poorly when uncertainties arise from long-term structural changes in the business environment. This approach is also difficult to apply when the problem involves many dependent uncertainties. Moreover, it does not easily incorporate risks that must be determined by expert judgment.

In practice, a utility is unlikely to use one approach exclusively. Most companies surveyed used a hybrid of two or even all three of the approaches. The best approach depends on the nature of the problem and the planning environment. The following are important factors in selecting an approach:

- Length of analysis. For example, a long-term forecast is required for evaluating capacity expansion decisions.
- Level of aggregation. This depends on the scope of the problem. The decision may be systemwide (capacity expansion) or narrower (DSM programs, interruptible rates for industrial customers).
- Level of detail. Does the decision maker need aggregate or detailed results? For example, peak energy will be sufficient for some forecasting problems; others will require hourly loads.
- Sources of uncertainty. Uncertainty can arise from changes in the business environment, such as technical innovation, or from random changes in the physical environment, such as weather.
- Degree of complexity. This depends on the major sources of uncertainty. The number of uncertainties and their interdependence will determine which approach best suits the problem.
- Available data. The utility may have a large number of data and/or many experts to draw on, or it may have limited informational resources.
- Staff. The utility may or may not have staff with expertise in the appropriate method.
- Objective. The utility may be trying to develop insights about what may happen in the future, or it may be making decisions directly.
- Audience. The intended audience (managers, executives, or regulators) and their backgrounds will affect the choice of method.

Stages of analysis

The scoping study noted that each approach has three phases: formulation, analysis, and communication. Each phase has several steps, though not every step appears in each approach. In a preliminary step common to all the approaches, the analyst determines what type of forecast is required (e.g., short or long term), what model or models are available, and how the results will be used.

The study identified eight steps in the planning or forecasting process. The first three make up the formulation phase:

▫ Step 1. Identify the key factors that are uncertain in the forecast and determine their relationships.

▫ Step 2. Tie the factors to variables in the planning or forecasting model.

▫ Step 3. Develop a reduced model as a proxy for the large forecasting model.

The next three steps make up the analysis phase:

▫ Step 4. Describe the uncertainty in the variables identified in the formulation phase.

▫ Step 5. Associate values with each of the variables; a range of values represents different conditions due to uncertainties.

▫ Step 6. Run the model (or reduced model) to generate outputs based on the values assigned in Step 5.

The final two steps make up the communication phase:

▫ Step 7. Communicate the results.

▫ Step 8. Integrate results into the decision-making process.

Each approach represents a selection of methods for the different steps. In practice, utilities often draw from all three approaches.

The scoping study concluded by making recommendations for future work. Table 1 lists the needs identified and the corresponding Phase 2 tasks to meet these needs. Phase 2 work now in progress includes preparation of a report on the three approaches, a videotape on scenario planning, a prototype scenario generation framework, and an analysis of the statistical uncertainty in a simple industrial end-use model.

Fuel Planning

Coal Quality Impact Model

by Arun Mehta, Generation and Storage Division

ABSTRACT *EPRI has developed the Coal Quality Impact Model (CQIM) to help coal procurement personnel reduce fuel costs, supplement long-term contracts, investigate low-sulfur coals for reducing sulfur dioxide emissions, and conduct evaluations of new coal supplies. CQIM helps utilities maximize the delivered heating value per dollar of fuel expenditure and minimize the operating costs associated with combustion. By using CQIM to select the most economical coal supplies on the basis of as-burned (rather than as-delivered) fuel costs, utilities can save millions of dollars.*

Coal composition and characteristics significantly affect nearly every facet of power plant operation, including auxiliary power requirements, forced-outage rate, maintenance costs, net plant heat rate, and a unit's ability to meet full load. Therefore, as-delivered fuel costs alone cannot properly reflect the relative economics of alternative coal supplies. To select the most cost-effective coal supply, a utility must be able to predict the impacts alternative coals would have on plant performance and overall power generation.

Available methods for analyzing coal quality impacts include large-scale test burns, pilot-scale burns, and detailed computerized engineering analyses. Full- or pilot-scale burns directly determine a unit's ability to accommodate a particular coal; they can be time-consuming and costly, however, especially if several coals are being considered. Moreover, translating observed performance into fuel-related costs can be extremely difficult. Therefore, a computer-based analysis is often the most practical way to evaluate alternative coals.

In 1985 EPRI initiated the development of a comprehensive state-of-the-art computer program for predicting coal quality impacts. The result is the Coal Quality Impact Model (CQIM™), which features detailed equipment performance models for all systems directly affected by coal quality. Available from EPRI as a commercial software product, CQIM has been designed for ease of use in a variety of utility applications. It is a flexible evaluation tool that can be applied at various levels of detail, depending on the sophistication of the user and the amount of input data available.

CQIM capabilities

Unlike computer programs that rely on numerous general correlations, CQIM is able to pre-

Table 1
SAMPLE CQIM PLANT INPUT DATA FOR SCREENING EVALUATION

General plant data	
Unit size (MW net)	500
Capacity factor	0.685
Auxiliary power requirements (MW)	40
Design net turbine heat rate (Btu/kWh)	8200
Excess air level (%)	20
Major equipment data	
Steam generator	
Maximum heat input per plant area ([million Btu/h]/ft²)	1.8
Maximum design gas exit temperature (°F)	1900
Tube spacing at furnace exit (in)	12
Maximum design flue gas velocity (ft/s)	60
Fuel preparation and firing	
Number of exhauster mills	6
Rated capacity of each mill (t/h)	60
Fans	
Number of forced-draft fans	2
Maximum flow per FD fan (acfm)	600,000
Number of induced-draft fans	2
Maximum flow per ID fan	950,000
Air heater	
Typical air heater leakage (%)	12
Corrected gas outlet temperature (°F)	300
Precipitator	
Total collecting plate area (ft²)	800,000
Design volumetric gas flow (acfm)	2,000,000
Ash handling	
Pressurized system for fly ash, capacity at normal operations (t/h)	50
Sluice system for bottom ash, capacity at normal operations (t/h)	20
Economic data	
Replacement energy cost (mills/kWh)	20
Limestone cost ($/t)	15

dict equipment performance impacts for a specific unit on the basis of the following input data:

- Configuration data, including available spares and system redundancy
- System and component capacities
- Historical unit and system performance
- System cycle times and auxiliary power requirements
- Historical maintenance and availability data
- System and component failure mode data

These data are used with CQIM's equipment performance models, which have been developed for each specific power plant system and, as applicable, each system component. CQIM then translates the detailed equipment performance predictions into fuel-related power generation costs, taking into account net plant heat rate, unit capability maintenance and availability, and waste disposal.

Changes in coal quality affect net plant heat rate through deviations in boiler efficiency, steam attemperation levels, flue gas temperatures, and auxiliary power requirements. CQIM predicts boiler efficiency for a given coal on the basis of calculations of latent heat, sensible heat, and unburned-carbon losses. (These losses are based on calculations of steam generator and air heater heat transfer performance, which affects the flue gas temperature and velocity profiles through the gas path.) To characterize changes in auxiliary power as a function of coal supply, CQIM considers system horsepower requirements as well as the frequency and level of use of components.

Coal supply to a plant is generally not uniform in quality but varies within a specified range. CQIM employs Monte Carlo derating analysis techniques to consider the impacts of coal quality variation on system capability. Monte Carlo techniques are used to approximate the variation of quality within the coal supply's specified range in order to determine derating magnitude and frequency as a function of time.

Coal quality affects equipment outage rates and hence overall unit availability and maintenance costs. CQIM predicts maintenance and availability impacts through the use of a modified UNIRAM model. This model uses historical data and correlations that relate component-level failure mechanisms to coal quality. It uses UNIRAM methodology to translate predicted component failures into occurrences of system and plant derating. All failures, regardless of their impact on availability, are considered in maintenance cost predictions.

CQIM predicts waste disposal costs for a variety of waste disposal configurations, including landfill and ponding. For units with flue gas desulfurization, it also considers dewatering capability and FGD system performance

CQIM contains a vast number of algorithms for supplementing data provided by the user. This default information is based on the data entered by the user, the overall plant configuration, the characteristics of the design coal, and established equipment design practices. CQIM users can therefore selectively collect and enter the most important input data in terms of their specific needs and experience and can rely on the model to supply default values for the remaining data. Of course, the more actual data used, the more accurate the CQIM predictions.

Table 1 illustrates the relatively simple input data requirements for conducting an initial screening evaluation of coal quality. The results can then be used to determine if further, more detailed input is necessary to more precisely predict unit performance. As the level of input data detail is increased, the CQIM evaluation becomes more sensitive to any unusual or limiting unit-specific design features.

CQIM evaluates alternative coals by comparing them with the current coal supply. Typical coal properties for input to the model include ultimate and proximate analyses, ash composition, ash fusion temperatures, and Hardgrove grindability numbers. CQIM can supplement incomplete sets of coal quality data on the basis of similar coal supplies.

Cost results from CQIM can be used to compare the economic viability of various coal supplies. In Figure 1 four coal supplies are compared on the basis of differential fuel-related generation costs as predicted by CQIM. As the figure shows, CQIM provides a comprehensive basis for evaluating coals.

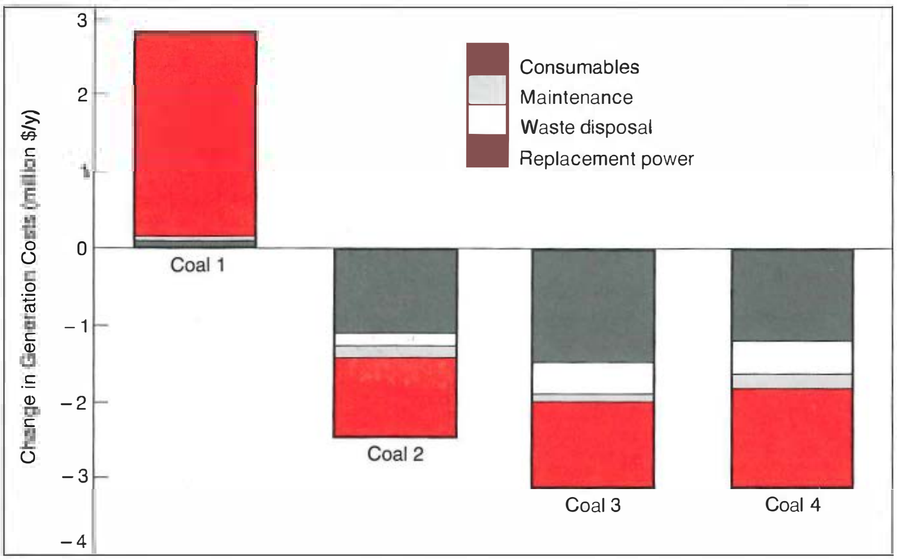
A notable CQIM capability is sensitivity analysis, which is useful in determining threshold limits for specific coal properties This type of analysis can be very useful in establishing coal procurement contract provisions for deviations in delivered coal quality.

CQIM validation

In addition to CQIM development, EPRI has supported many activities to transfer the model effectively to the utility industry and to ensure that it remains a state-of-the-art tool.

One of the most significant efforts involves

Figure 1 These CQIM economic results predict how the use of four alternative coals would increase or decrease the generation costs associated with the current coal. The breakdown of cost components illustrates the comprehensive level of analysis possible with CQIM, which is sensitive to all significant factors in coal quality evaluation.



model validation through a host utility program. In this program, which is nearing successful completion, 12 utilities have worked with EPRI to develop case studies to validate the CQIM equipment performance models. CQIM performance and cost predictions are compared with historical data and actual utility operating experience, and any discrepancies are used to modify the program modules and improve CQIM's overall predictive capability. As shown in Table 2, the case studies cover a wide range of unit designs and coals.

As a result of significant industry interest in CQIM, its use has not been confined to the host utility participants. Approximately 40 other utilities have participated in the project as prerelease users. Several of them have applied the model in making spot-market coal purchases and establishing contract range limits. Among the many practical CQIM applications identified by the utilities are the following:

- Evaluating potential coal supplies (both spot market and long term) according to overall fuel-related generation costs
- Establishing coal specifications and property range limits for specific generating units to minimize generation losses and operating problems
- Quantifying the performance and economic impacts of variations in key coal properties, such as heating value, sulfur content, and ash content
- Identifying coal quality impacts on maintenance and availability costs; providing information to help project future manpower requirements and identify systems that will need increased attention
- Quantifying the advantages/disadvantages of switching, blending, and cleaning coals; determining the optimal degree of coal cleaning and blending
- Evaluating the performance of, and economic trade-offs between, high-sulfur coals (which require flue gas desulfurization) and compliance coals
- Screening alternative coals to eliminate the least suitable and minimize the number of test burns to be performed
- Developing strategies for acid rain legislation
- Providing valuable technical information for use in engineering studies—for example, information on how equipment modifications will affect overall unit performance and economics

Future enhancements

CQIM is commercially available from the Electric Power Software Center (EPSC) for Digital

Table 2
HOST UTILITY PLANTS FOR CQIM VALIDATION

Utility	Unit	Boiler	Particulate Removal Device	SO_2 Removal Device
Centerior Energy	Eastlake Unit 5 (660 MW)	Supercritical	Cold precipitator	None
East Kentucky Power Cooperative	Spurlock Unit 2 (500 MW)	Subcritical	Hot precipitator	Wet lime
Houston Lighting & Power	W. A. Parish Unit 8 (535 MW)	Subcritical	Fabric filter	Wet limestone
New England Electric System	Brayton Point Unit 3 (575 MW)	Supercritical	Cold precipitator	None
Northern States Power	Sherco Unit 1 (700 MW)	Subcritical	Particulate scrubber	Wet limestone
Pennsylvania Electric	Conemaugh Units 1 and 2 (900 MW)	Subcritical	Hot precipitator	None
Public Service Company of Indiana	Cayuga Units 1 and 2 (535 MW)	Subcritical	Cold precipitator	None
Southern Company Services	Watson Unit 4 (250 MW)	Subcritical	Cold precipitator	None
Tennessee Valley Authority	Cumberland Unit 1 (1300 MW)	Supercritical	Cold precipitator	None
Union Electric	Rush Island Unit 1 (575 MW)	Subcritical	Cold precipitator	None
Virginia Power	Mount Storm Unit 1 (550 MW)	Subcritical	Cold precipitator	None
Wisconsin Power & Light	Nelson Dewey Unit 2 (105 MW)	Subcritical (cyclone)	Hot precipitator	None

Equipment VAX systems; commercial versions of the program for IBM VM and MVS operating systems are being finalized. Also, the EPSC has a simplified version of the program available for the IBM PC.

In addition to commercialization efforts, EPRI plans to further refine and enhance the usefulness of CQIM. In response to comments received from the utility users group, CQIM is currently being converted to run on an IBM-compatible 80386 desktop computer. This program version will incorporate additional features that promote ease of use and provide the user with greater flexibility in integrating the model into utility-specific coal procurement practices.

An expert system will be incorporated into CQIM to facilitate data input and aid in output interpretations. Also, the ability of CQIM to consider full-scale, bench-scale, and pilot-scale data will be expanded. This will enable a utility to use the model to address the economics associated with a coal being test-burned. In addition, such data can be used to improve CQIM's predictive capabilities. New correlations for steam generator performance with respect to slagging, fouling, and the formation of nitrogen oxides are planned as part of other EPRI programs.

Through improved understanding of how coal properties affect unit performance and fuel-related costs, a utility can potentially save millions of dollars by means of improved coal acquisition practices and improved unit operations. CQIM will be an essential tool for developing that understanding.

Environmental Performance Assessment

Coal Ash Use Sites

by Ishwar Murarka, Environment Division

ABSTRACT *The wider use of coal combustion by-products for embankments, structural fills, roadbeds, and the like depends in part on the development of information about their environmental performance in these applications. EPRI is sponsoring field investigations to measure long-term changes in soil, vegetation, groundwater, and surface water around coal ash use sites. The results of two recently completed, limited field studies show localized changes due to the migration of ash constituents.*

Close to 80 million tons of fly ash, bottom ash, slag, and scrubber sludge are produced annually by the electric utility industry. Markets for 15–25% of these by-products of coal combustion have been developed. However, wider use of these residues is limited by transportation costs, by the lack of a reliable and quality-controlled supply (which certain uses require), and by concerns that the residues may contaminate groundwater, soil, and surface water.

In a 1988 report to the Congress, the Environmental Protection Agency encouraged the increased use of coal combustion wastes when that can be achieved in an environmentally acceptable manner. Even though coal ash has been used at some 300 sites in the United States, however, measurements of the environmental effects are scarce or nonexistent. To help meet the need for information, in 1987 EPRI initiated a study on the environmental effects of ash use (RP2796). This research, cofunded by Empire State Electric Energy Research Corp., is aimed at measuring long-term changes in soil, groundwater, vegetation, and surface water quality around embankments, structural fills, roadbeds, and amended soils.

In the first phase of the study (1987–1989), Radian Corp. conducted field investigations to measure changes in the chemical composition of groundwater, soil, surface water and vegetation at two coal ash use sites: an embankment site in Waukegan, Illinois, and a structural fill site in Little Canada, Minnesota. All field sampling, sample analysis, and data analysis were completed by November 1989. Detailed technical reports on the two sites are being prepared.

The field investigations at each site consisted of two steps: (1) a reconnaissance effort involving one-time, limited sampling, and (2) detailed sampling over a network within a limited area.

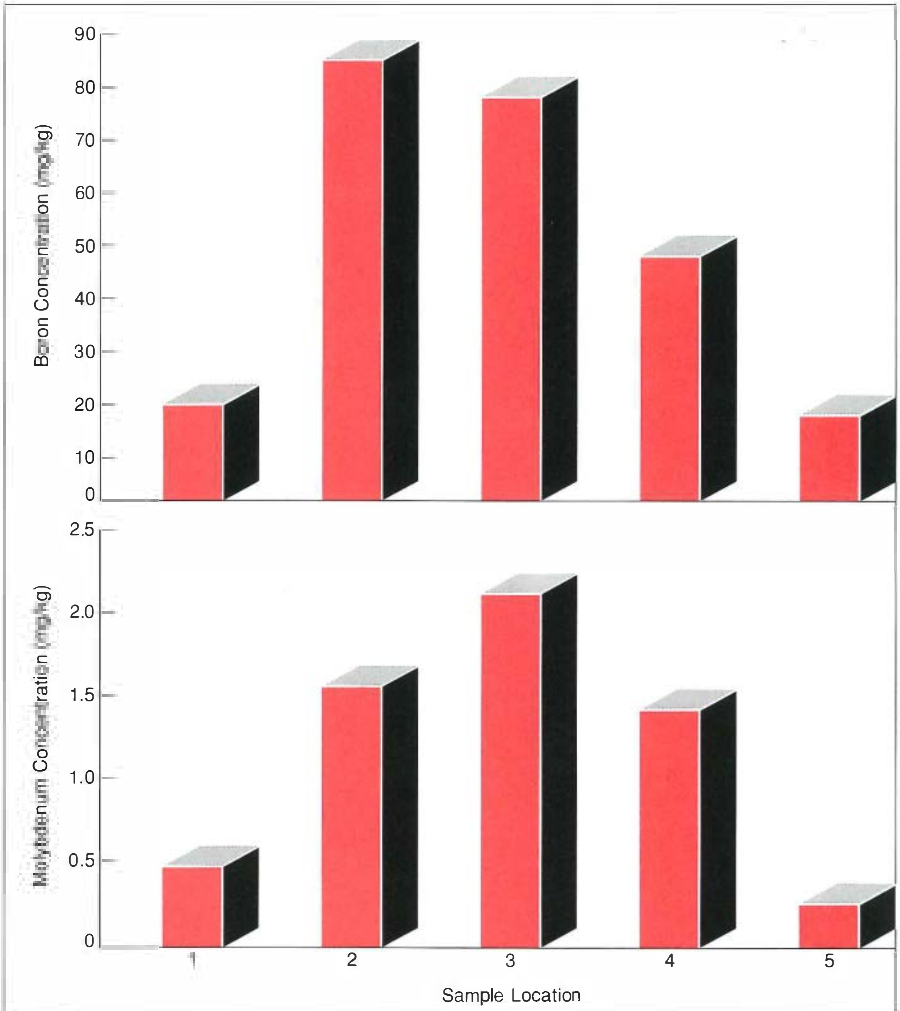
The reconnaissance effort, conducted in 1987, began with the installation of piezometers for estimating the hydraulic gradient and direction of groundwater flow. Then groundwater-monitoring wells were installed upgradient, below the coal ash placement zone, and downgradient along a transect in the groundwater flow path. Samples of soil, groundwater, surface-runoff water, and vegetation were collected and analyzed for water quality parameters and elemental composition.

The more detailed sampling effort was performed in 1988. At each site 25 groundwater-monitoring wells, 12 porous-cup lysimeters, and 2 pan-type lysimeters were installed beneath the ash to monitor chemical changes in the saturated and unsaturated zones. Groundwater wells were screened at two depths. Samples were analyzed for a broad range of water quality parameters (pH, Eh, alkalinity, alpha radioactivity, and concentrations of chloride, fluoride, sulfate, nitrate, phenol, arsenic, boron, barium, cadmium, cobalt, calcium, magnesium, chromium, copper, lithium, molybdenum, nickel, selenium, strontium, and zinc).

Waukegan site assessment

The Waukegan site, located in northern Illinois a few hundred meters west of Lake Michigan, has nearly level topography, consisting of dune sands and back beach sediments deposited by the lake. A state highway segment and overpass embankment were constructed in 1970–1972 with approximately 350,000 cubic meters (500,000 metric tons) of coal ash from Commonwealth Edison's Waukegan generating station. The ash embankment is composed principally of ASTM Class F fly ash, although minor amounts of bottom ash, clay, and other fill materials were also used in the construction of the highway interchange.

Figure 1 Distribution of boron and molybdenum in broadleaf plants along the Waukegan sampling transect. Plants growing directly on ash (locations 2 and 3) show the greatest uptake and accumulation in tissues.



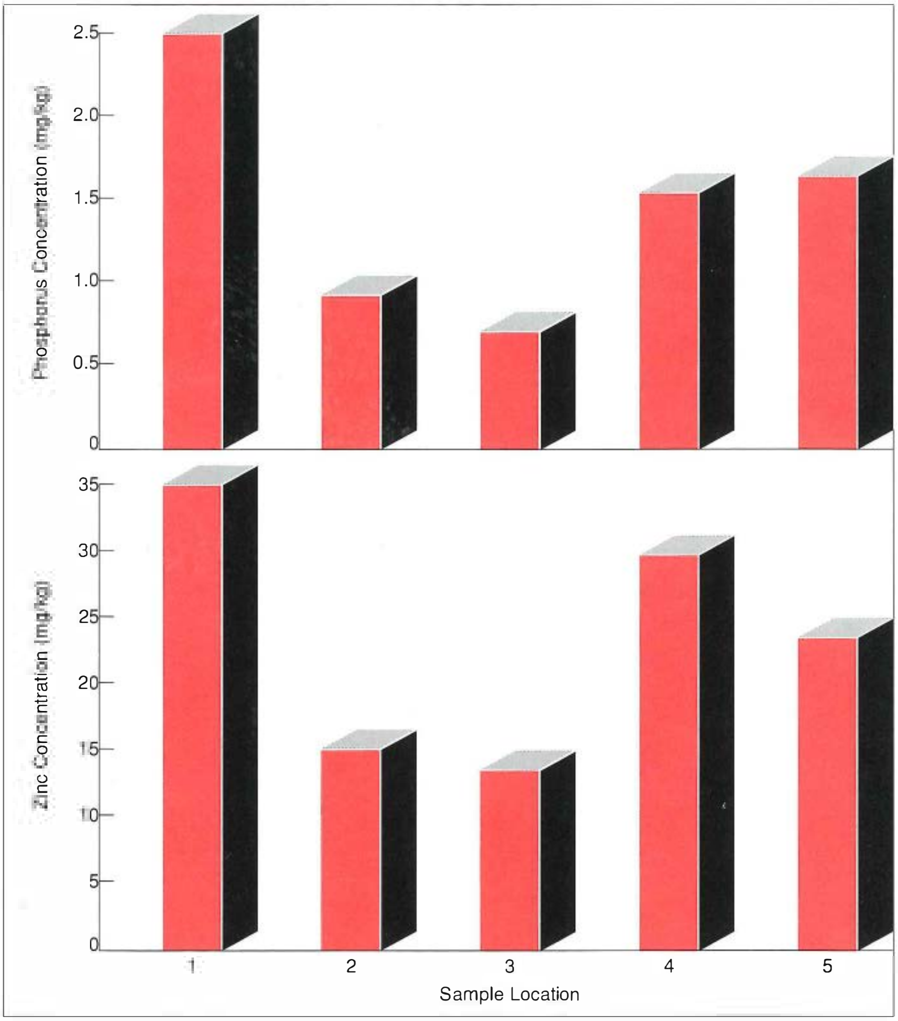
Several soil core samples were taken at the sites. Subsamples representing several depths were analyzed in the laboratory to measure the accumulation and/or deposition of ash constituents. In general, the data indicate that the sandy soils did not attenuate constituents leached from the ash. The underlying soils showed no contamination by, or accumulation of, the ash constituents. The reason is that sandy soils lack the necessary properties for adsorption, being very low in clay, cation exchange capacity, and hydrous oxides of iron and manganese.

Two types of vegetation, grasses and broadleaf plants, were sampled to examine the effect of differences in rooting characteristics. Broadleaf plants typically have taproot systems that extend relatively deep into the soil. Grasses, on the other hand, have fibrous root systems that are concentrated closer to the surface. Elemental concentrations in plant tissues were measured for samples collected at several spatial locations. Both accumulations and deficiencies of elements were found in plant tissues, but the plants had no apparent visual symptoms of either type of change.

Chemical analysis identified the accumulation of several elements of coal ash origin in plant tissues. Figure 1, for example, shows concentrations of boron and molybdenum in broadleaf plant tissues. Compared with samples from location 1 (the control location), samples from locations 2 and 3 (directly on ash) had increased concentrations of these two elements. The plant-tissue concentrations decreased at locations 4 and 5, where plants grow on soil overlying the coal ash deposit. The following elements showed increased concentrations in tissues of plants growing directly on ash:

- Broadleaf plants: boron, molybdenum, and nickel

Figure 2 Distribution of phosphorus and zinc in grasses along the Waukegan sampling transect. These results illustrate the reduction in availability and uptake of certain plant nutrients.



- Grasses: aluminum, boron, molybdenum, and strontium

Chemical analysis also identified decreases in concentrations of some elements in plant tissues. For example, phosphorus and zinc concentrations in grass tissues were lowest in samples from locations 2 and 3 (Figure 2). The decreased concentrations in plant tissues are a direct result of the decreased availability of these elements due to high pH in the soil-ash mixture. These elements showed decreased concentrations in plants growing on ash:

- Broadleaf plants: barium, calcium, magnesium, manganese, and zinc
- Grasses: magnesium, phosphorus, and zinc

At the Waukegan site, groundwater flows in an easterly direction beneath the embankment toward Lake Michigan. On the basis of measurements made in 1988, the groundwater flow velocity is estimated to be between 4.9 and 11.5 meters per year. Data obtained during the four sampling dates show consistent trends over time for ash-derived constituents in groundwater and soil-pore water.

Data for the wells that transect the embankment show that compared with samples from upgradient wells, sulfate levels are two times higher and boron levels are over an order of magnitude higher in groundwater samples obtained beneath the ash. Other species from coal ash that appear to have leached into the shallow groundwater zone include arsenic, barium, calcium, chloride, iron, lithium, manganese, magnesium, potassium, sodium, and strontium. The concentration of these ash-derived constituents rapidly dissipates with distance away from the embankment and at greater depths in the groundwater below the ash.

Samples of soil-pore liquids obtained from lysimeters within the ash embankment showed elevated concentrations of the same species that had elevated concentrations in the shallow groundwater beneath the ash. The concentrations of certain ash-derived species (boron, calcium, potassium, molybdenum, sulfate, strontium, and vanadium) were significantly higher in the soil-pore liquids, however. This contrasts with the Little Canada ash fill site, where major ions were present in about equal concentrations in soil-pore liquids and groundwater. The Waukegan ash embankment appears to have been leached to a lesser extent than the Little Canada ash fill. This finding is not surprising, since the paved road surface and steep embankment side slopes at the Waukegan site favor runoff and reduced infiltration into the ash.

Little Canada site assessment

The Little Canada structural fill site is a level, currently undeveloped area adjacent to a small industrial park in a suburb north of St. Paul, Minnesota. Together with the industrial park, the site was originally a low-lying, poorly drained area; it was reclaimed by filling it with coal ash. The filling operation began in 1978 and was completed in 1980. About 39,000 cubic meters (50,000 metric tons) of ash were used over the approximately 1-hectare site. The ash came from three coal-fired power plants owned by Northern States Power. The alkaline coal ash has cementitious properties and is classified as a Class C fly ash according to the ASTM test method.

In contrast to the Waukegan site studies, the analysis of extracts of coal ash and soils from the Little Canada fill site revealed that some elements (cobalt, manganese, molybdenum,

Table 1
GROUNDWATER DATA, LITTLE CANADA SITE
(samples collected August 11, 1988)

Sampling Location*	Boron Concentration (mg/L)	Sulfate Concentration (mg/L)	Calcium Concentration (mg/L)
Upgradient (average)	0.5	175	187
Well B1			
Shallow	5.8	1992	460
Deep	0.6	88	250
Well B2 (shallow)	4.3	4432	500
Well B3 (shallow)	9.1	4844	290
Well B4			
Shallow	4.3	667	390
Deep	0.6	4	150
Downgradient			
Shallow	0.6	21	230
Deep	0.6	74	240

*Distances from the upgradient sampling location to the other locations are as follows: to well B1, 60 meters; to well B2, 83 meters; to well B3, 108 meters; to well B4, 133 meters; to the downgradient location, 212 meters.

strontium, and zinc) migrated from the coal ash and were attenuated by the underlying soils. These attenuation trends are best seen in the decreasing trace element (strontium and molybdenum) concentrations with depth. It is postulated that the trace elements coprecipitated with manganese compounds as a response to changing pH and redox conditions underneath the ash-soil contact zone.

Results from the two-year investigation show consistent trends for ash-derived constituents in the shallow groundwater and in soil-pore water. Compared with results for the control location and the deep groundwater zone, elevated levels of potassium, sodium, calcium, magnesium, sulfate, chloride, boron, fluoride, molybdenum, and strontium were measured in shallow-depth groundwater-monitoring wells installed in the fill area. Table 1 shows selected results. In soil-pore liquid samples obtained from lysimeters beneath the ash, the same 10 species were found in approximately the same concentra tions as in the shallow groundwater samples.

In contrast, the groundwater wells installed in the deeper layer of the aquifer showed no change in the chemical composition of the water These data provide a basis for concluding that vertical mixing and depth of penetration of leachates are restricted to a very shallow groundwater zone. Further, the results indicate a very localized change in groundwater quality due to the migration of water-soluble constituents from the ash.

Groundwater data collected during this investigation indicate that ash-derived constituents are present in groundwater immediately beneath the ash fill. However, it is not likely that leaching of the ash in response to surface water infiltration and downward percolation is the cause. The lack of rainfall at the site (less than an inch was recorded during the period of groundwater sampling in 1988) ensures very little infiltration. Field measurements show seasonal fluctuation of the groundwater table, with at least one monitoring well exhibiting a groundwater elevation above the coal ash. Therefore, researchers hypothesize that the presence of ash-derived constituents in groundwater is due to fluctuating groundwater levels in the zone near the ash-soil contact. At normal rates of rainfall and groundwater recharge in the site vicinity, the water table is expected to come in contact with ash and allow leaching of ash constituents by direct dissolution reactions.

Conclusions and future studies

Similar trends were observed for aqueous concentrations of elements in shallow groundwater and pore water samples at the two sites over two sampling events. Concentrations of soluble constituents released from the ash were measured in the shallow groundwater layer immediately beneath the ash zone (boron, calcium, magnesium, molybdenum, sodium, chloride, fluoride, sulfate, and possibly strontium); however, none of the heavy metals present in the ash moved into the deeper soils, pore water, or groundwater. The results also show that the concentrations of ash-derived constituents that migrated into the shallow groundwater dissipate rapidly with distance away from the ash deposits.

The following conclusions can be drawn from the study results:

- The release of highly soluble constituents from the ash occurs periodically when fluctuating groundwater encroaches on the ash.
- Ash leachate constituents have not impacted the deeper groundwater zones below the ash or the groundwater downgradient of the ash deposits.
- Limited attenuation of the leached constituents occurs in the underlying soils.
- Vegetation growing on the coal ash exhibits increased uptake of some constituents and decreased uptake of others. The reasons are (1) changes in the concentration of elements available to plants as a function of the addition of ash constituents to the soil, and (2) changes in soil pH induced by the ash additions, changes that affect the solubility of some plant nutrients (both ash-derived elements and elements native to the soil).

On the basis of the limited studies at the Waukegan and Little Canada sites, it is clear that there is a need for a statistically sound data base on environmental performance of waste use sites. General conclusions for all use practices cannot be drawn from research at just two sites. For this reason, field measurements at a cross section of sites are planned for the future.

In the second phase of studies under RP2796, research will focus on the waste use categories of embankments, roadbeds, and ash-amended soils. Nine sites will be selected to provide diverse environmental, geographic, and waste use combinations. These studies will measure several chemical constituents (inorganic, organic, and radioactive) in groundwater and surface water samples, as well as uptake and accumulation by nearby vegetation. Radon emissions will also be measured at sites where gases may accumulate. Hydrology and geochemistry will be characterized to quantify the distribution of mobile and attenuated constituents. Analysis of the field measurements will provide assessments of the environmental performance at each site. Assessment manuals and databooks will be prepared and published to assist in defining parameters for the environmentally acceptable use of coal combustion residues.

Diagnostics

Gas Turbine Combustion Viewing System

by Henry Schreiber, Generation and Storage Division

ABSTRACT *The higher efficiency of modern gas turbines is due largely to the cooling and materials technology that has made it possible to raise the temperature of the combustion gases flowing through the turbine. To maintain high reliability and availability in the face of these more severe operating conditions, diagnostic instrumentation is needed that can provide early indication of a system malfunction, so that corrective action can be taken before there are adverse physical effects on the equipment. The combustion viewing probe is one of several hot-gas-path diagnostic instruments developed by the EPRI Combustion Turbine Program intended to fulfill this function.*

Gas turbines are a popular option for capacity increases; published estimates indicate that 40,000–75,000 MW of new gas turbine generating capacity will be added in the next 20 years. The large, stationary gas turbines offered by the major manufacturers in the 1980s range in capacity from 78 to 150 MW in simple cycle and up to 220 MW in combined cycle. Net efficiencies are in the 32–33.5% range for the simple-cycle offerings and in the 44–49% range for the combined cycles. Technical advances and improved design philosophy have increased availability and reliability to the high-80% to mid-90% range, while capital costs are in the $200–250/kW range for simple cycle and the $400–600/kW range for a combined cycle.

Lead times are relatively short compared with those for other generation options, and the available sizes of capacity-increase increments allow the utility to add capacity parallel to load growth. The higher firing temperature required to achieve the high efficiencies necessitates the use of new diagnostics.

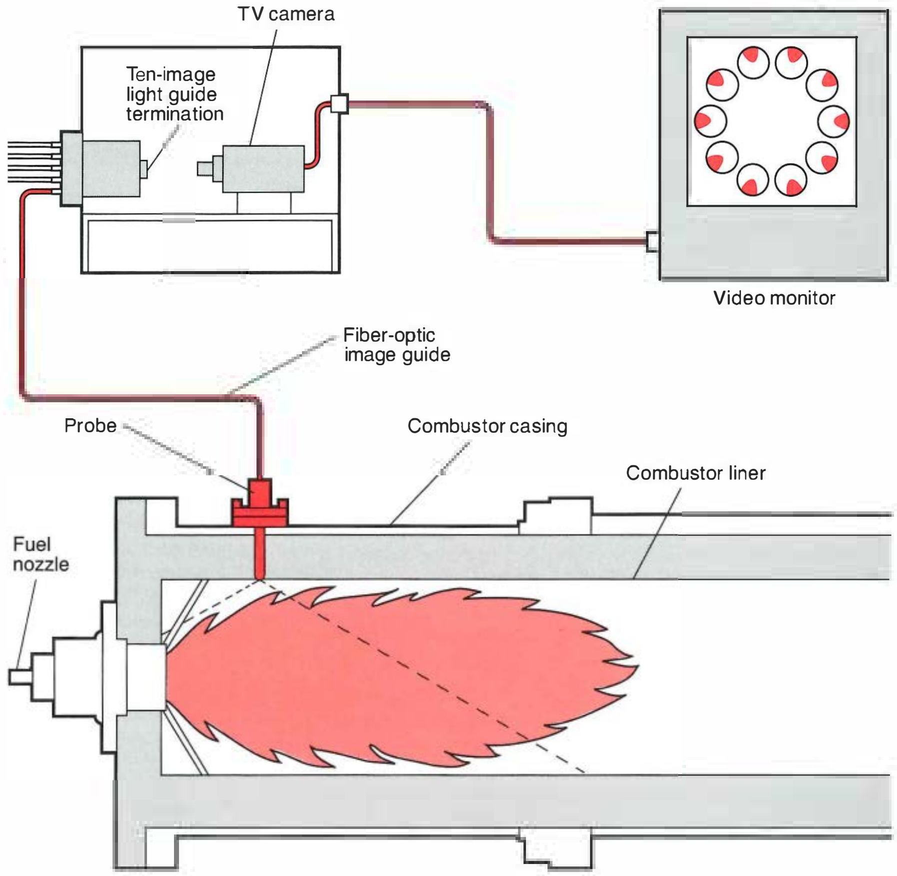
Research prototypes

A proof-of-concept prototype of a combustion viewing probe was built by United Technologies Research Corp. (UTRC) under EPRI contract (RP2102-2). This single-sensor probe was installed on unit 41 (a General Electric MS7001B combined-cycle unit) at the T. H. Wharton plant of Houston Lighting & Power. The instrument consisted of a heat-resistant probe containing a 120° wide-angle lens and fiber-optic cable. The image was scanned by a remote television camera. The probe looked into one of the 10 combustion chambers on the engine. This high-resolution probe produced an image composed of 80,000 pixels and allowed real-time observation of combustor light-off, load changes, and shutdown. During this evaluation period, investigators used the probe to observe combustor performance phenomena such as delayed ignition, crossfire tube operation, flame instability, bimodal flame deployment, and abnormal attachment of the flame to the fuel nozzle and the upstream end of the combustor. These are the types of flame anomaly of interest to gas turbine operators, as well as to engine designers.

The image quality obtained with this research prototype probe proved highly suitable for gas turbine diagnostics in that it showed flame location and geometry in detail. The cost, however, was beyond the usual range for an instrument that would be commercially marketable to utilities. EPRI therefore undertook a follow-on project with UTRC to develop a lower-cost probe using new fiber-optics technology that would still provide sufficient image definition and probe durability. This redesigned combustion viewing system is intended for use as part of a permanently installed array. The array consists of one viewing probe mounted on each of the 10 combustors on a GE MS7001 engine. Gas turbine unit 33, part of a combined-cycle unit at HL&P's Wharton plant, was chosen as the test engine for the full, 10-probe array.

The probes are mounted so that they do not protrude into the combustor liner and therefore are not exposed directly to the flame. The probe operating temperature remains close to the temperature of the engine's compressor discharge air, which acts as a purge and coolant as it blows by the probe shaft into the combustor dilution air hole, where the probe is mounted. Figure 1 is a schematic diagram of one combustor and probe in the 10-probe arrangement.

Figure 1 Schematic diagram of one combustor and probe in a 10-probe array on a gas turbine unit at HL&P's Wharton plant. The probe looks into one of the 10 combustion chambers and picks up flame images, which are then displayed on a video monitor for real-time observation of combustor performance.



Production prototype

The 10-probe production-scale prototype has a 0.3-mm spherical lens optically coupled to a 0.3-mm, 2000-strand coherent fiber-optic cable, or image guide. The 2000-pixel image produced on a video screen provides sufficient detail to show flame instability, combustion delay, crossfire tube activity, and general flame location. These diagnostic observations enable an operator to detect combustion anomalies promptly.

The 10-probe production prototype was installed on Wharton unit 41 and started up the week of May 29, 1989. The viewing system demonstrated its potential value immediately upon startup, when an ignition delay of over two minutes was observed in one of the 10 combustors. Ignition delays produce thermal stress and allow unburned fuel to accumulate. This latter effect can result in a hazardous uncontrolled pressurization of the exhaust ductwork.

The current production-model combustion viewing system displays the flames in all 10 combustors simultaneously and in the same relative position as the combustors on the engine. This display is satisfactory for purposes of operation and maintenance. The next phase of the project will be to develop a fully commercial prototype unit that incorporates system design modifications to further reduce the cost and make the probes easier to fabricate on a commercial scale. The design of the probes will be made more rugged to make field maintenance of the viewing system easier and reduce the risk of damage to the probes from rough handling. Another anticipated design enhancement will make it possible to enlarge the image of any one flame and observe it as it changes in real time. With these design enhancements, the combustion viewing probe system will be ready to be offered to utilities commercially. It will be particularly useful on the new generation of higher-firing-temperature gas turbines. EPRI will develop specifications that will enable the buyer of a new gas turbine to incorporate the combustion viewing probe into the purchase specifications submitted to the gas turbine manufacturer.

New Contracts

Project	Funding/ Duration	Contractor/EPRI Project Manager
Customer Systems		
Power Electronics Systems Analysis (RP2951-9)	$183,800 19 months	Georgia Tech Research Institute/*M. Samotyj*
Development of Advanced Off-Peak or Base-Loaded Electric Water Heaters (RP2958-4)	$227,000 9 months	Vaughn Thermal Corp./ *C. Hiller*
Integrated Value-Based Planning (RP2982-4)	$604,200 20 months	Putnam, Hayes & Bartlett, Inc./*P. Hanser*
Heat Recovery Chiller Field Demonstration (RP2983-8)	$131,900 13 months	W. S. Fleming & Associates Inc./*M. Blatt*
Installation and Operation of Chiller Heat Recovery System (RP2983-9)	$75,700 13 months	Pacific Homes Inc./ *M. Blatt*
Advanced Electric Transportation Systems Technology Assessment (RP3025-1)	$148,300 9 months	Bechtel Group, Inc./ *B. Banerjee*
Assessment of Capacitor Technology and Applications in Power Electronics and Control Systems (RP3088-1)	$56,700 9 months	University of Missouri at Columbia/*B. Banerjee*
Exploratory Research		
New Chemical Alternative Refrigerants (RP8000-48)	$155,900 35 months	Clemson University/ *P. Joyner*
Computerized Corrosion Behavior Information for Utility Applications (RP8002-19)	$749,900 34 months	National Association of Corrosion Engineers/ *B. Syrett*
A Comprehensive Investigation of the Inorganic Constituents of Coal and Coal Derivatives (RP8003-20)	$220,000 22 months	University of Kentucky/ *S. Yunker*
Molecular Structure of Coal Macerals (RP8003-21)	$250,000 22 months	Southern Illinois University/*S. Yunker*
Characterization and Reconstruction of Coal-Gasifying Mixed Cultures (RP8003-23)	$286,400 36 months	Arctech Inc./*S. Yunker*
Critical Currents, Weak Links, and Flux Pinning Studies of Oxide Superconductors (RP8009-5)	$814,500 36 months	University of Wisconsin/ *T. Schneider*
Fundamental Studies on Critical Current Density in Materials (RP8009-11)	$936,600 60 months	Stanford University/ *D. Sharma*
Development of Ceramic Superconductors for Electric Power Applications (RP8009-12)	$195,600 13 months	University at Buffalo Foundation, Inc./ *T. Rodenbaugh*
Improved Superconducting Ceramics for High-Current Applications (RP8009-15)	$159,000 15 months	U.S. Department of Energy/*W. Bakker*
Generation and Storage		
Market Evaluation for Fly Ash Fillers (RP2422-20)	$63,100 6 months	Kline & Company Inc./ *D. Golden*
Combustion Turbine Coatings Guidebook (RP2465-2)	$172,100 17 months	Southwest Research Institute/*R. Frischmuth*
Mass Culture of Algae Utilizing CO_2 From Stalk Gases (RP2612-11)	$509,200 18 months	University of Hawaii at Manoa/*J. Berning*
Short-Rotation Woody Crop Trials for Energy Production in North Central United States (RP2612-12)	$80,000 25 months	Energy Performance Systems Inc./*J. Berning*
On-Line Monitoring for the Plant Auxiliary Power System (RP2626-3)	$432,700 24 months	Bechtel Power Corp./ *J. Stein*
Commercialization Potential of AFBC Concrete (RP2708-4)	$193,500 9 months	Dearborn Chemical Company Ltd./*D. Golden*
Controls and Automation Technical Support (RP2710-7)	$67,300 12 months	Automation Technology Inc./*S. Divakaruni*
Materials Testing for CAES Well Applications (RP2894-6)	$59,700 8 months	Radian Corp./*B. Mehta*
Nuclear Power		
Service Water Assistance Program (RP2495-13)	$108,200 14 months	Texas Utilities Electric Co./ *N. Hirota*
New York–New England Seismic Experiment (RP2556-53)	$50,000 12 months	U.S. Geological Survey/ *J. Schneider*
Source Parameters and Tectonics of Large Earthquakes in Stable Continental Regions (RP2556-54)	$55,000 12 months	Memphis State University/ *J. Schneider*
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LWR License Renewal Lead Plant—BWR (RP3075-1)	$2,000,000 60 months	Northern States Power Co./ *R. Burke*
Seismic Instrumentation of Mexican Power and Industrial Facilities (RP3090-3)	$79,000 2 months	PRISIS/*R. Kassawara*
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BWR Stability Support (RP3114-7)	$100,000 11 months	Computer Simulation and Analysis Inc./*R. Galer*
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EPRI Project Manager: J. Kesselring

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EPRI Project Manager R. Nakata

Proceedings: Second Biennial PFBC Power Plants Utility Conference
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EPRI Project Manager: D. Golden

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EPRI Project Managers: O. Tassicker, S. Drenker

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EPRI Project Manager: B. Louks

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VIPRE-01: A Thermal-Hydraulic Code for Reactor Cores, Vols. 1–3 (Revision 3)
NP-2511-CCM-A Computer Code Manual (RP1584-1); Vol. 1, $25; Vol. 2, $25; Vol. 3, $25
Contractor: Battelle, Pacific Northwest Laboratories
EPRI Project Manager: G. Srikantiah

Linear and Nonlinear Response of Structures and Equipment to California and Eastern United States Earthquakes
NP-5566 Final Report (RP2556-8); $32.50
Contractors: Risk Engineering Inc.; Stanford University
EPRI Project Managers: A. Singh, J. Stepp, R. Kassawara

Below Regulatory Concern Owners Group: Individual and Population Impacts From BRC Waste Treatment and Disposal
NP-5680 Interim Report (RPB101-11); $1000
Contractor: Rogers and Associates Engineering Corp.
EPRI Project Manager: P. Robinson

Demonstration of Reliability-Centered Maintenance, Vol. 2: First Annual Progress Report From San Onofre Nuclear Generating Station
NP-6152 Vol. 2 Interim Report (RP2970-3); $32.50
Contractors: Southern California Edison Co.; ERIN Engineering and Research Inc.
EPRI Project Manager: J. Gaertner

Demonstration of Reliability-Centered Maintenance, Vol. 3: First Annual Progress Report From Ginna Nuclear Station
NP-6152 Vol. 3 Interim Report (RP2970-1); $32.50
Contractors: Rochester Gas and Electric Corp.; Advanced Technology Engineering Systems Inc.
EPRI Project Manager J. Gaertner

Matrix Database of EPRI Experimental Projects on Small-Break Loss-of-Coolant Accidents
NP-6180 Final Report (RP2639-1); $32.50
Contractor: Intermountain Technologies Inc.
EPRI Project Manager: J. Sursock

Methods of Ultimate Load Analysis of Concrete Containments: Phase 3
NP-6262-M Final Report (RP2172-1); $25
Contractor: ANATECH Research Corp.
EPRI Project Manager: H. Tang

Proceedings: EPRI Power Plant Valves Symposium II
NP/GS-6327 Proceedings (RP2519-1); $40
Contractor: Maintenance Equipment Application Center
EPRI Project Manager: B. Brooks

Sourcebook for Chemical Decontamination of Nuclear Power Plants
NP-6433 Special Report; $32.50
EPRI Project Managers: C. Wood, C. Spalaris

Field Studies on Intergranular Attack
NP-6455 Final Report (RPS306-21); $32.50
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: C. Welty

Enriched Boric Acid for PWR Application: Cost Evaluation Study for a Twin-Unit PWR
NP-6458 Final Report (RP2648-1); $5000
Contractor: Westinghouse Electric Corp.
EPRI Project Managers: J. Santucci, C. Spalaris

Relay Behavior at the Perry Nuclear Power Plant During the 1986 Earthquake in Leroy, Ohio
NP-6472 Final Report (RP2849-2); $25
Contractors: NUTECH Engineers Inc.; Stevenson Associates
EPRI Project Manager: R. Kassawara

EPRI Workshop on Fire Protection in Nuclear Power Plants
NP-6476 Final Report (RP2969); $40
EPRI Project Manager: J. Sursock

Evaluation of Burnup Credit for Dry Storage Casks
NP-6494 Interim Report (RP2813-8); $25
Contractor: Virginia Power
EPRI Project Manager: O. Ozer

Advanced PWR Steam Generator Digital Feedwater Control System
NP-6497-M Final Report (RP2126-4); $40
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: J. Naser

CALENDAR

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

DECEMBER

4–6
Advanced Computer Technology for the Power Industry
Scottsdale, Arizona
Contact: Murthy Divakaruni, (415) 855-2409

5–6
Global Atmosphere and Public Health
Washington, D.C.
Contact: Ralph Perhac, (415) 855-2572

7–8
Industrial Load Shaping
Palo Alto, California
Contact: Paul Meagher, (415) 855-2420

JANUARY 1990

17–18
Marketing Program Planning and Evaluation
Salt Lake City, Utah
Contact: Tom Henneberger, (415) 855-2885

FEBRUARY

21–23
EPRI Food Service Symposium
New Orleans, Louisiana
Contact: Karl Johnson, (415) 855-2183

MARCH

6–9
International Symposium: Performance, Improvement, Retrofitting, and Repowering Fossil Fuel Power Plants
Washington, D.C.
Contact: Gary Poe, (415) 855-8969

20–23
EPRI–EPA Symposium: Transfer and Utilization of Particulate Control Technology
San Diego, California
Contact: Ramsay Chang, (415) 855-2535

21–23
2d National Conference and Exhibition on Power Quality for End-Use Applications
Burlingame, California
Contact: Marek Samotyj, (415) 855-2980

MAY

1–3
1st International Symposium on Biological Processing of Coal
Orlando, Florida
Contact: Stanley Yunker, (415) 855-2815

8–11
1990 SO_2 Control Symposium
New Orleans, Louisiana
Contact: Paul Radcliffe, (415) 855-2720

JUNE

11–13
Applications of Power Production Simulation
Washington, D.C.
Contact: Mark Lauby, (415) 855-2304

JULY

29–August 3
International Conference: Indoor Air Quality and Climate
Toronto, Canada
Contact: Cary Young, (415) 855-2724

AUGUST

28–30
International Conference: Measuring Waterborne Trace Substances
Baltimore, Maryland
Contact: Winston Chow, (415) 855-2868

SEPTEMBER

18–20
Conference: Condenser Technology
Boston, Massachusetts
Contact: John Tsou, (415) 855-2220

OCTOBER

15–17
Incipient Failure Detection: Predictive Maintenance for the 1990s
Philadelphia, Pennsylvania
Contact: John Scheibel, (415) 855-2850

Authors and Articles


Johnson


Blatt


Schurr


Rabl


Lannus


Dau


Lang

Lighting the Commercial World (page 4) was written by Leslie Lamarre, science writer, assisted by two staff members of EPRI's Customer Systems Division.

Karl Johnson manages research on energy systems for commercial buildings. He has been with EPRI since 1977, following two years as coordinator of industrial and energy services for the Palo Alto (California) utilities department. Still earlier, he worked for eight years in energy management for Stanford University. Johnson graduated in economics from Denison University and earned an MS in mechanical engineering at Stanford.

Morton Blatt, manager of the Commercial Program, came to EPRI in 1985 after seven years with Science Applications International, where he worked on the development of energy-efficient HVAC equipment. Before 1978, he worked for 12 years with General Dynamics on cryogenic systems and heat transfer analysis. Blatt graduated in mechanical engineering from Cooper Union, earned an MS in industrial engineering at New York University, and has a master's degree in business administration from San Diego State. ■

Electrification: Key to Manufacturing Productivity (page 16) was written by Mary Wayne, communications consultant, in cooperation with **Sam Schurr**, retired deputy director of EPRI's Energy Study Center.

Schurr was with EPRI for a total of 12 years, from 1973 to 1975 directing the division originally responsible for both environmental and economic studies, and from 1979 to 1988 working in energy studies. He also worked with Resources for the Future on two occasions, first as director of its energy and minerals program and later as codirector of energy policy research. Before 1954 he was with several federal agencies. Schurr has two degrees in economics from Rutgers. ■

Integrated Home Automation (page 24) was written by John Miller, communications consultant, aided by feature editor Ralph Whitaker and two research managers of EPRI's Customer Systems Division.

Veronika Rabl is the manager of the Demand-Side Planning Program established early this year. She had been a project manager for seven years, with primary responsibility for residential and commercial load management research. Before coming to EPRI in 1981, she worked for almost seven years at Argonne National Laboratory, much of the time in technology assessment, including a year on assignment to the DOE Office of Energy Systems Research. Rabl graduated in physics from the Weizmann Institute of Science in Israel. She also has a PhD from Ohio State.

Arvo Lannus has managed the Residential Program for more than seven years. He joined EPRI in 1980 after six years with Gordian Associates, where he was director of advanced technology, responsible for research on heat pumps and energy use in buildings. Earlier he was on the chemical engineering faculty of Cooper Union School of Engineering. Lannus has a BS in chemistry and a PhD in chemical engineering, both from Drexel University. ■

The NDE Center: Celebrating a Decade of Achievement (page 32) was written by David Boutacoff, *Journal* feature writer, who drew on information supplied by two staff members of EPRI's Nuclear Power Division.

Gary Dau heads the Component Reliability Program and has been the Institute's principal liaison with the NDE Center since it opened in 1980. He initiated an NDE program at EPRI in 1975 while on loan from Battelle, Pacific Northwest Laboratories, and managed it when he joined the EPRI staff in 1977. He had been with Battelle since 1965. Dau has a BS in mechanical engineering from the University of Idaho, a PhD in nuclear engineering from the University of Arizona, and an MS in technology management from MIT.

James Lang, manager of the Plant Operations and Maintenance Program since 1986, joined EPRI in 1979 to manage research in the Steam Generator Project Office; he later worked in the Nuclear Safety Analysis Center. He earlier was with the Navy's Nuclear Power Directorate for nine years, becoming director of the reactor plant valve division. Lang graduated in physics from Michigan State. ■

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