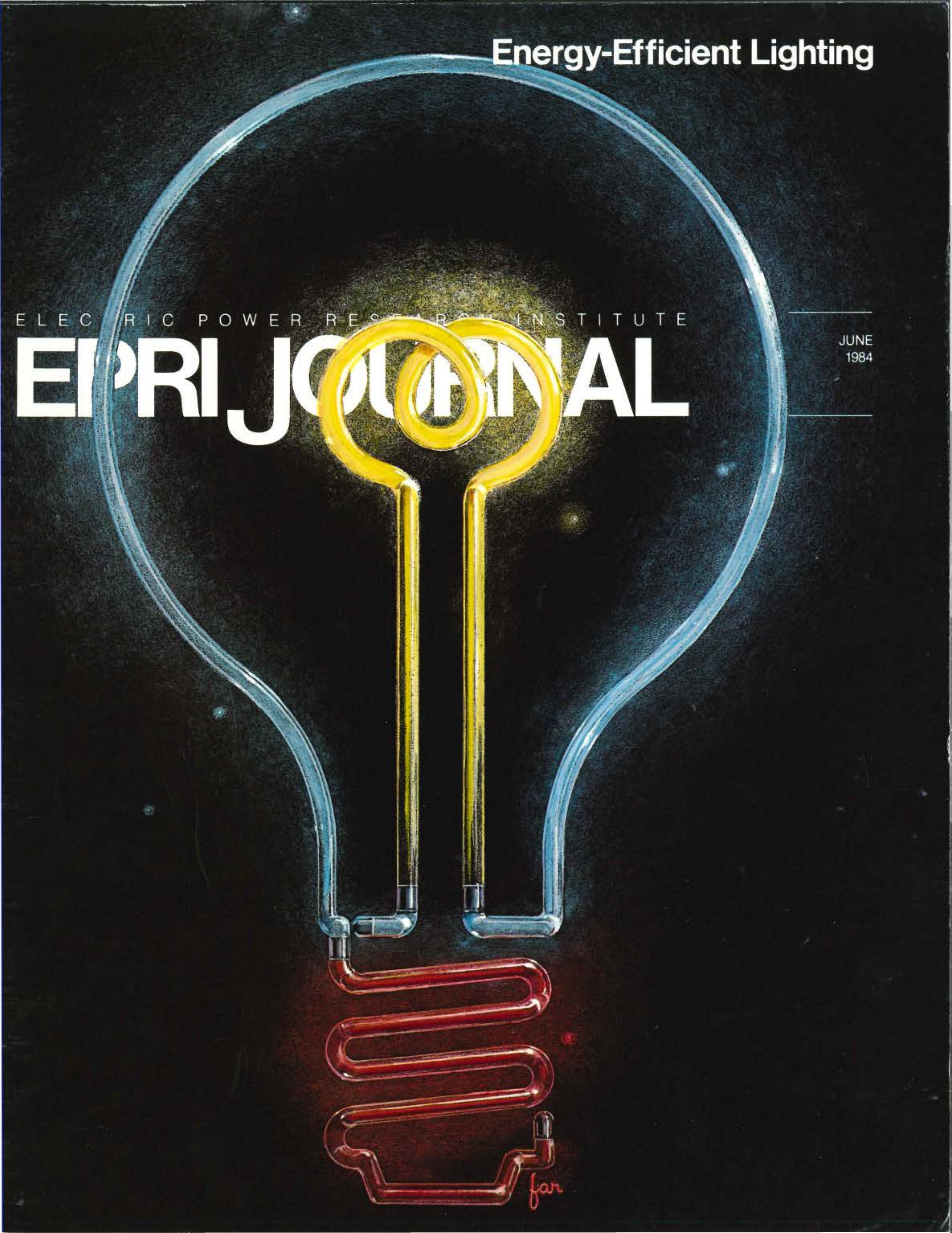
Energy-Efficient Lighting

ELECTRIC POWER RESEARCH INSTITUTE
EPRI JOURNAL
JUNE 1984



EPRI JOURNAL is published monthly, with the exception of combined issues in January/February and July/August, by the Electric Power Research Institute. The April issue is the EPRI *Annual Report*.

EPRI was founded in 1972 by the nation's electric utilities to develop and manage a technology program for improving electric power production, distribution, and utilization.

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Cover: Today's energy-efficient lighting strategies range from higher-efficiency lamps to sophisticated controls integrated into energy management systems.

EPRI JOURNAL

Volume 9, Number 5 June 1984

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Lighting the Future

If you're like most people, you probably take lighting for granted: You flip a switch and there it is. However, lighting—society's earliest and most basic use of electricity—has been undergoing some major changes recently. Today's lighting, which uses some 420 billion kWh of the electricity generated every year, is significantly different from what it was in the past. And lighting and the way we control it will continue to evolve in the future.

Many of the changes are taking place because the world is changing the way it gets its work done. For example, a report is no longer written on paper at one's desk but on the display screen of a computer terminal. This may be thought of as replacing a horizontal task with a vertical task, and lighting should be adjusted accordingly. To accommodate this and other changes, the emphasis in lighting is shifting from general illumination to task-oriented illumination. Our industries are changing as well; traditional industries that required low lighting levels are being replaced by high-technology industries, such as microelectronics, which require higher lighting levels for the assembly of minute parts. This precision assembly also requires improved directional lighting not usually associated with industrial work.

This month's cover story on lighting illustrates a number of technological advances that are being developed to address these changes and that are also making lighting a more efficient user of electricity. The story makes clear that from the basic improvement of lamps and their application, to the fixtures we use with them, to the equipment we use to control them, lighting is progressing at a rapid pace.

Because lighting consumes approximately 20% of the nation's electricity, electric utilities are directly affected by these changes. Lighting is especially significant in the commercial sector, where it can represent 40–50% of a building's total load and often is a major contributor to the building's cooling load. Directly and indirectly, commercial and industrial lighting contribute significantly to the daytime peak demand of electric utility systems. Efficient lighting systems, controls, and design, in addition to helping businesses manage their energy bills, now offer an opportunity for utilities to reduce this peak demand and thereby defer construction of new power plants.

Until recently, electric utility activities in lighting have focused on providing advice on levels of illumination and assisting with street-lighting programs. Revenue from the delivery of this service has been a staple in the menu of services electric utilities offer. However, lighting addresses only the delivery of light to a visual environment, which is only one aspect of the far broader issue of illumination. Visual acuity, perception, and human response are interrelated phenomena that affect the value and benefits derived from lighting. Recent developments in this broader field of research have put increased emphasis on how lighting affects productivity in the workplace. The recent establishment of the Lighting Research Institute has recognized the need for a comprehensive and multidisciplinary effort to address all these issues in illumination. EPRI and the electric utility industry are major participants in this national effort to address the broadest range of lighting issues.

Lighting is on the threshold of an exciting era. There will be many changes in how we light today's environment at work and at home. EPRI's lighting programs will offer utilities the opportunity to go beyond the simple delivery of electricity and assist their customers in managing energy use more effectively.

Thomas R. Schneider

Thomas R. Schneider, Director
Energy Utilization and Conservation Technology
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Authors and Articles

Light is the unrivaled manifestation of electricity. Other energy forms can heat our buildings, cook our food, propel vehicles, and run machinery and processes. But by and large, nothing but electricity can produce the light that people command with the flick of a switch. This month's cover story, **Evolution in Lighting** (page 6), surveys a number of advances in technology that together could halve the electric energy needed for lighting. Nadine Lihach, senior feature writer, wrote the article largely from interviews with Stephen Pertusiello, who manages EPRI research in lamps, illumination controls, and space design factors.

On loan to EPRI's Energy Management and Utilization Division since November 1983, Pertusiello came from Consolidated Edison Co. of New York, Inc., where he worked for 11 years, successively in substation construction, load management technology, and conservation services. An electrical engineering graduate of the Polytechnic Institute of New York, Pertusiello earned an MS in management there as well.

■

Activated in the core of a nuclear reactor and then deposited throughout the primary coolant system, minute impurities cause a gradual buildup of radioactivity that inhibits maintenance and repair operations. **Decontaminating Reactor Coolant Systems** (page 16) describes one of the newest and most effective R&D products for attacking the problem. Feature editor Ralph Whitaker wrote the article, guided by Christopher Wood, who originated the research for its cosponsors, EPRI and Great Britain's Central Electricity Generating Board (CEGB).

A program manager for chemical and radiation control research in EPRI's Nuclear Power Division since March 1982, Wood formerly was in the Research Division of CEGB's Berkeley Nuclear Laboratories for 14 years, including 11 years as head of the radiation chemistry section. From 1966 to 1968 he was a research chemist with E. I. du Pont de Nemours & Co., Inc. Wood graduated in chemistry from University College in London and earned a PhD in physical chemistry at the University of Leicester.

■

Design conservatism is not necessarily design confidence when it comes to the high-pressure, high-temperature components of fossil fuel power plants. Even in nominally identical units, different regimens of pressure and temperature produce different accumulations of creep and fatigue, strains that influence the integrity and life expectancy of parts and their welded connections. **The Life of Metal Under Stress** (page 24) surveys EPRI's R&D into nondestructive means for locating, categorizing, and measuring strain, monitoring its growth, and predicting repair or replacement requirements. Members of two EPRI technical groups aided Taylor Moore, feature writer, in developing the article.

Ramaswamy Viswanathan, project manager for mechanical metallurgy, has been with the Materials Support Program since June 1979, following 14 years with the Westinghouse Electric Corp. R&D center, where he worked in applications and evaluations of metals for nuclear and high-temperature systems. On leave from Westinghouse for one year, he managed metallurgy research at the R&D center for Bahrat Heavy Electricals Ltd. in India. Viswanathan graduated in chemistry from Madras University and later earned a degree in metallurgy at the Indian Institute of Science. He holds ME and PhD degrees in metallurgy from the University of Florida and Carnegie-Mellon University, respectively.

John Dimmer is project manager for R&D in fossil fuel boilers and their auxiliaries. He has been with the Fossil Plant Performance and Reliability Program since he joined the Coal Combustion Systems Division in June 1977. Dimmer came to EPRI after 15 years with Detroit Edison Co., where he became head of a central staff task force on plant availability. Dimmer graduated in electrical engineering from the University of Detroit.

Pertusiello

Wood

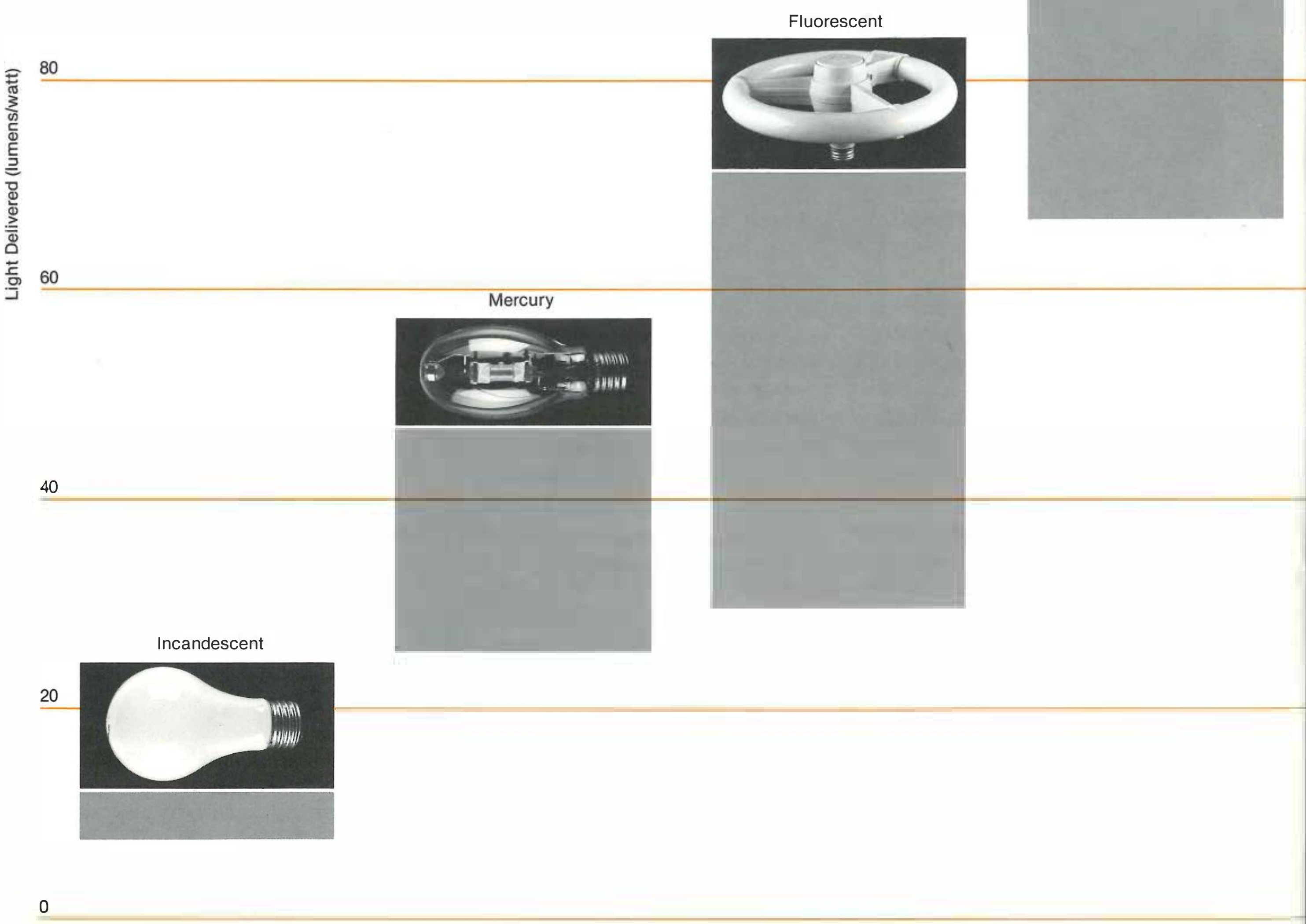
Viswanathan

Dimmer

EVOLUTION IN LIGHTING

Lights consume 20–25% of the nation's electricity, establishing strong incentives to develop more-efficient lighting strategies. Attention is turning to where, when, and how we light our environment, and the potential savings add up to half the lighting load nationwide.

Some types of lamp are more efficient than others, but characteristics other than energy consumption may dictate where they can be used.



Photos courtesy of General Electric Co.

High-pressure sodium

Electric lights once blazed 24 hours a day in multistoried office buildings. Brightness flooded factories and department stores, nighttime streets, and even the empty rooms of homes. No one thought to turn the lights off when they were not needed; electricity was too inexpensive to put individual switches on office lights, to dim superfluous lights in factories and window displays, to flip a switch when exiting a room.

The lights add up

Then, in the early 1970s, energy prices jumped, and suddenly, the nation could no longer afford to let lights burn indiscriminately. The billions of lamps in offices, factories, stores, streets, and homes were consuming about a quarter of the nation's electricity.

Consumers—especially in the commercial and industrial sectors—tried to cut back. Early conservation attempts included wholesale reductions in numbers of existing lamps and replacement of high-wattage, high-lumen-output lamps with lower-wattage, lower-output lamps. But it quickly became apparent that lighting was too important to safety and productivity to be arbitrarily reduced. Lighting bills had to be cut, yet necessary lighting levels had to be maintained.

Today, after some 10 years of hard work by lamp and fixture manufacturers, architect-engineers, utilities, government agencies, and others, the seemingly impossible goal of cutting back lighting energy requirements while maintaining necessary lighting levels is being achieved by illuminating only what has to be illuminated.

Consider office lighting. In most offices, fluorescent lamps are placed symmetrically overhead in sufficient numbers to achieve a relatively high level of general illumination. This practice overlooks the fact that office workers may not require this level of general illumination. It is more likely that their paperwork requires a high level of specific illumination, and the rest of the office a lower level. By reducing general lighting and directing specific lighting onto the task at hand, energy can be saved with no risk to health or productivity.

"Consumers need to suit the lighting to the task," stresses Stephen Pertusiello, manager of lighting research in EPRI's Energy Management and Utilization Division. "We're not asking anyone to do with less light," adds James Jewell, lighting services administrator at Pacific Gas and Electric Co., a regular adviser to EPRI's lighting program, and 1984–1985 president of the Illuminating Engineering Society of North America. "We just need to use it more efficiently."

Suiting lighting to the task is what today's energy-efficient lighting strategies are all about—tactics that range from simply dousing unnecessary lights, to installing lamps that produce more lumens of light from fewer watts, to introducing such sophisticated lighting controls as occupancy sensors and energy management systems, to designing new buildings that supplement electric light with daylight wherever possible. Some of these strategies are for new buildings only, but most can be applied anytime, anywhere. According to recent estimates, a grand total of 50% of the 420 billion kWh a year used for lighting could be saved through energy-efficient strategies, all without imposing any hardships on productivity, safety, or esthetics.

The energy saved will do more than just conserve fuel, explains Pertusiello. Both commercial and industrial lighting contribute heavily to the daytime peak demand of electric utility systems; in some areas, lighting totals 40% of the daytime commercial peak. Worse, the considerable waste heat created by lighting must then be removed by air conditioning, which boosts daytime peak demand further. By reducing this peak demand, energy-efficient lighting may allow utilities to defer construction of costly new power plants, a savings ultimately passed on to the consumer.

Getting the most from lighting

The catalog of strategies for making lighting more energy-efficient begins with the most basic lighting equipment: bulbs, or lamps, as the lighting industry prefers to call them. There are three types of lamp—the incandescent, the fluorescent, and the high-intensity discharge—and each has its own special characteristics.

Incandescent lamps, the widely used lamps that most people picture when they think of light bulbs, are unfortunately the least efficient of the three. The incandescent lamp produces light by using electricity to heat a coiled tungsten filament in a vacuum bulb until the filament becomes so hot that it glows. By the time the filament glows enough to light a room, some 90% of the electric energy drawn by the lamp has been wasted as heat. To add to the inefficiency, minute particles of the burned tungsten coil migrate to the inner surface of the glass bulb as the incandescent lamp ages, causing the bulb to darken and ultimately reducing the amount of light that leaves the lamp by as much as 20%. Because of their inherent inefficiencies, incandescent lamps consume 42% of the nation's lighting energy while providing only 16% of the illumination.

Fluorescent lamps are far more energy-efficient than incandescents. They convert electricity directly into light by using an electric charge to excite gaseous atoms within a phosphor-coated tube. The charge is sparked in the lamp's ballast and flows through cathodes in either end of the tube. The resulting gaseous discharge causes the phosphor coating on the inside of the tube to fluoresce, or emit light. Because fluorescent lamps bypass the heat stage, they are up to five times more efficient than incandescents; they also boast a longer life, burning as long as 20,000 hours, compared with 750–1000 hours for incandescents.

More efficient than either the incandescent or the fluorescent lamps are the high-intensity discharge (HID) lamps. HID lamps consist of a sealed arc tube that pairs two electrodes with a metal that can be vaporized and ionized to conduct electric current in an arc from one electrode to another. Most HID lamps are about six times more efficient than incandescent lamps, which is even more efficient than fluorescents; they also last longer in the bargain. Three basic types of HID lamp are available, distinguished by the metal they contain: mercury, metal halide, and high-pressure sodium.

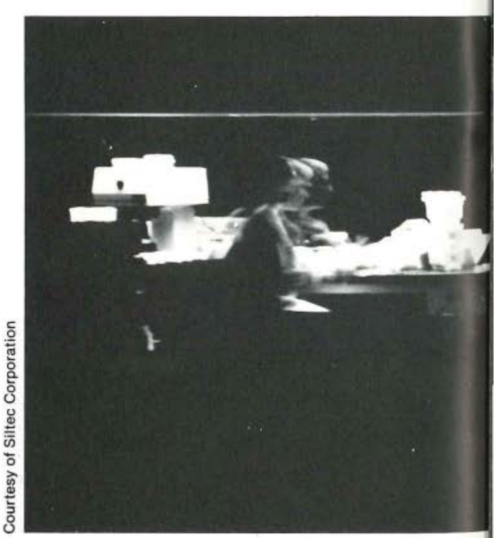
Changing the light bulb

Fluorescent and HID lamps are more efficient than incandescents, but it is not always possible to trade the incandescent lamps for fluorescent lamps or the fluorescent lamps for HID lamps. Lamps have characteristics other than energy consumption that dictate where they can be used. The incandescent lamp, despite its inefficiency, is universally popular because of the way it makes colors appear, a quality called color rendition. Incandescent light emphasizes reds and downplays blues, bringing out pleasing ruddy tones in faces, food, clothing, and other surroundings. For this reason, incandescent lamps are used almost exclusively in homes and such commercial settings as restaurants and department store displays.

Fluorescent lamps, for all their efficiency, are generally handicapped by a color rendition that tends to emphasize blue tones that many people consider unflattering. As a result, fluorescents are taboo in most homes except for occasional lighting over a kitchen sink or a workbench. Instead, fluorescent lamps are extensively employed in commercial and industrial settings where efficiency is more important than appearance. Another drawback to fluorescent lamps is that they require ballasts—small transformers that regulate electric current—to operate the lamp, and ballasts necessitate the fluorescent lamp fixtures familiar to all office denizens. Few homeowners would be willing to exchange their decorative table and floor lamps for these fixtures.

The Task at Hand

In a changing world, lighting solutions are changing, too. Conventional overhead office lighting may no longer be efficient when horizontal tasks (like reading a report on a desktop) are replaced by vertical tasks (like reading the same report on a computer terminal). General industrial fluorescent lighting



Courtesy of Siltec Corporation

may be displaced by specific task lighting that illuminates highly visual jobs, such as silicon wafer fabrication. Sometimes lighting can be adapted to work in new situations, such as lowering the wattage and improving the color rendition of high-pressure sodium lamps for use in office settings.

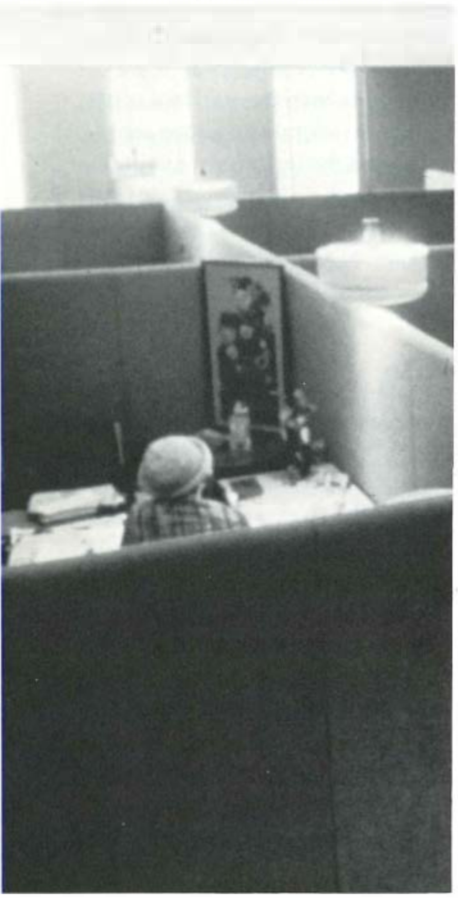
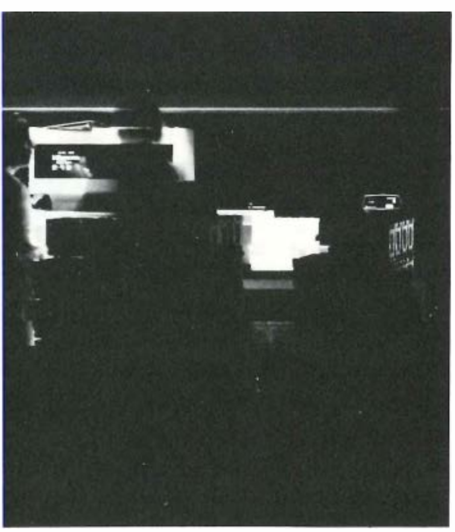
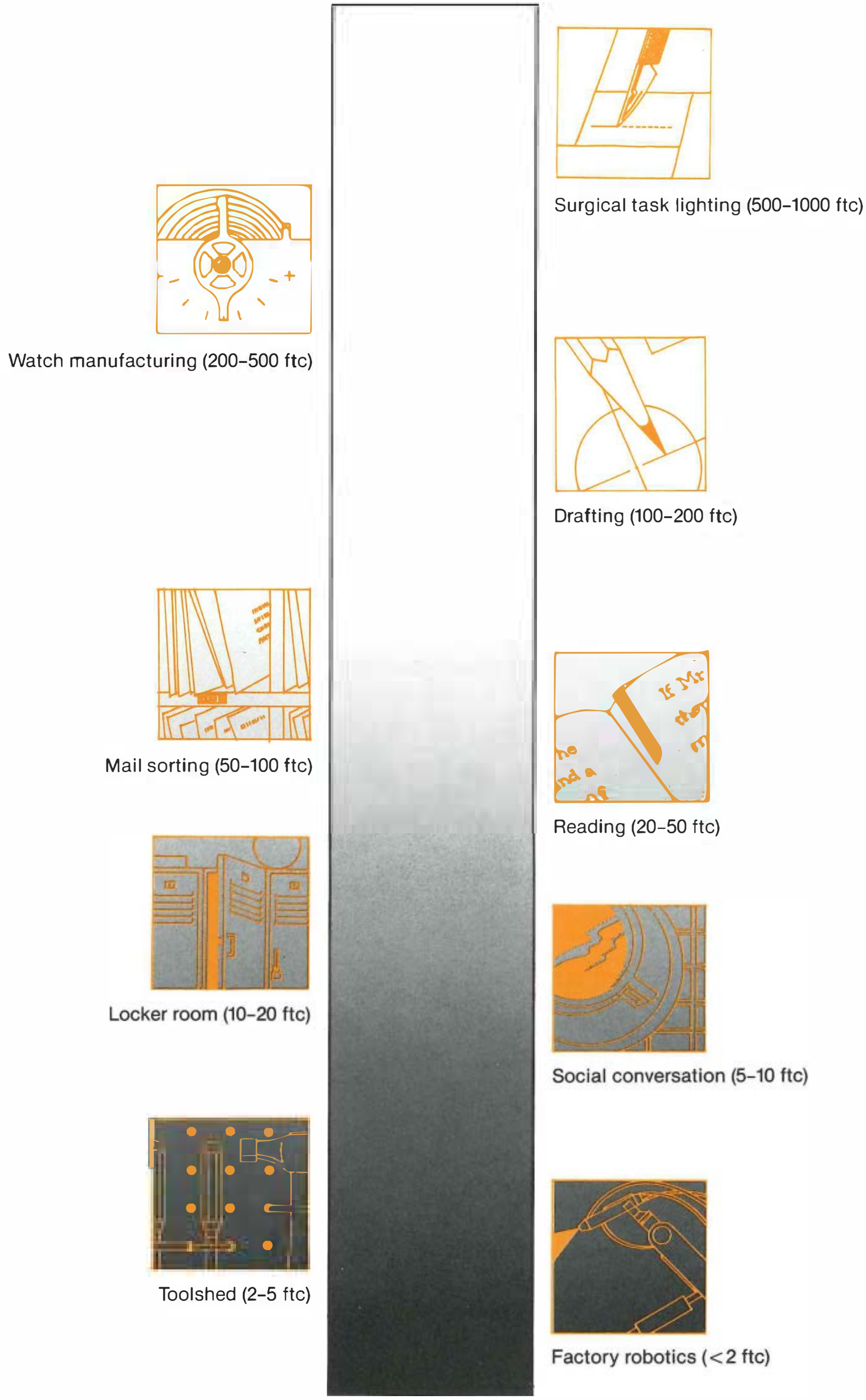


Photo courtesy Georgia Power Co.



Different tasks require different lighting levels, and one sure way to save electricity is to match the lighting to the task. Lighting engineers use footcandles—a unit equaling the illuminance at a point 1 ft from a single candle—to express how much lighting different tasks require. Surgeons need 500–1000 footcandles to do their exacting work; jewelers require 200–500 footcandles; reading in home or office calls for 20–50 footcandles; and factory robots don't need any light at all.



HID lamps, the most efficient of all, have traditionally been available only in relatively high wattages of 450–1000, and most have comparatively poor color rendition. As a result, HID lamps have been relegated mostly to lighting large outdoor areas (e.g., parking lots, arenas, and streets) or large indoor areas (e.g., industrial warehouses and factories).

"Nevertheless, recent developments in the lighting industry are causing some important changes in the lamps consumers use," says Pertusiello. Incandescent lamps that deliver more light per watt of energy than conventional incandescents have been offered in the last few years by General Electric Co., GTE/Sylvania Corp., and North American Philips Corp., the three major U.S. lamp manufacturers. This savings is made possible by improved filaments and bulbs. Increasing numbers of these new lamps are being purchased by homeowners, although the old-style incandescents still dominate the residential market.

Fluorescent lamps are also making inroads into the residential market: a number of manufacturers have released a fluorescent lamp–ballast combination that can be screwed into a standard incandescent lamp fixture. This innovation lets homeowners take advantage of fluorescent's energy savings without having to invest in new fixtures to accommodate fluorescent lamps. The novel lamp-ballast combination is made possible by tiny new solid-state electronic ballasts.

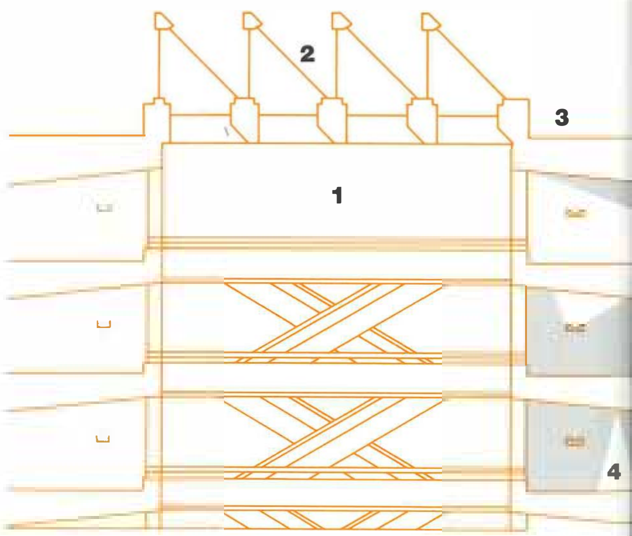
Homeowners still dubious about fluorescent color rendition now have dozens of shades of fluorescent lamps to choose from, some of which closely mimic the effects of incandescent lighting. These lamps cost more than the standard cool-white lamps that dominate fluorescent lamp sales, and the inner bulb coating that gives them their improved color rendition also exacts a penalty in lighting efficiency. Nevertheless, homeown-

Skylighted atrium at Lockheed Missiles & Space Co.'s new office building in Sunnyvale, California, designed by Leo A. Daly Co., San Francisco. Daylighting added nearly $3 million extra to the $50 million cost of the building, but Lockheed expects to recover that figure in lighting bill savings over a 6½-year period.

Photo courtesy Leo A. Daly Co.

Letting the Sun In

A special kind of building is required to successfully team daylight with electric light for energy savings. Daylit buildings are a carefully calibrated combination of architectural features and lighting controls. This schematic highlights some basic daylighting features, although designs vary widely from building to building and place to place, depending on such variables as local climate and site conditions.



1 Atrium brings light to the inner core of a building.

2 Skylights admit light into an atrium.

3 Building orientation is critical; the narrow sides of a rectangular building should face east-west to minimize glare and heat from the rising and setting sun; the long sides of a building should face north-south to collect maximum overhead light.

ers may find these fluorescent lamps an acceptable, energy-efficient alternative to incandescent lamps.

While fluorescents are infiltrating the residential market, HID lamps are edging their way into the commercial market that fluorescents now monopolize. HID lamps of 150 W and less have recently been developed by lamp manufacturers, along with new techniques for HID color correction. Reduced wattages and improved colors have convinced a number of commercial customers to try HID lighting in office settings. For example, high-pressure sodium vapor fixtures have been installed in Georgia Power Co.'s new corporate headquarters in Atlanta, Georgia.

Fixing the fixtures

Changes in lamp fixtures can also promote energy efficiency in lighting. For example, the ballasts in fluorescent and HID fixtures have always been standard iron-core, wire-coil transformers, which inescapably waste some of the energy that flows through them in the form of heat. In recent years, solid-state electronic ballasts have been developed that can operate fluorescent lamps 20–25% more efficiently than can conventional ballasts. These ballasts, which can be retrofitted into existing fluorescent and HID fixtures, are now available from a number of manufacturers, and work to advance them continues. EPRI recently commissioned Lawrence Berkeley Laboratory to evaluate the performance of these newcomers, including such criteria as efficiency, electrical effects, flicker, and regulation.

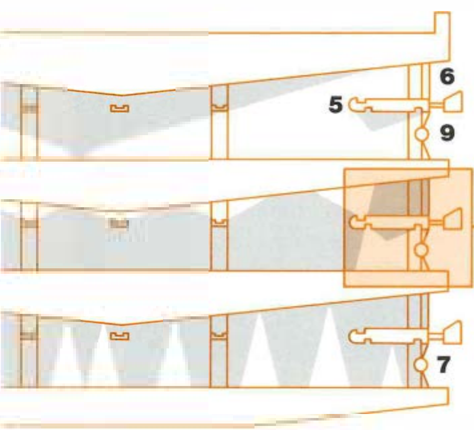
Another way to upgrade the efficiency of lighting fixtures is to improve fixture reflectors. Fluorescent lamps, for instance, shine about half of their light up into the top portion of the fixture, called a reflector. Much of that light is then reflected back down into the room, but

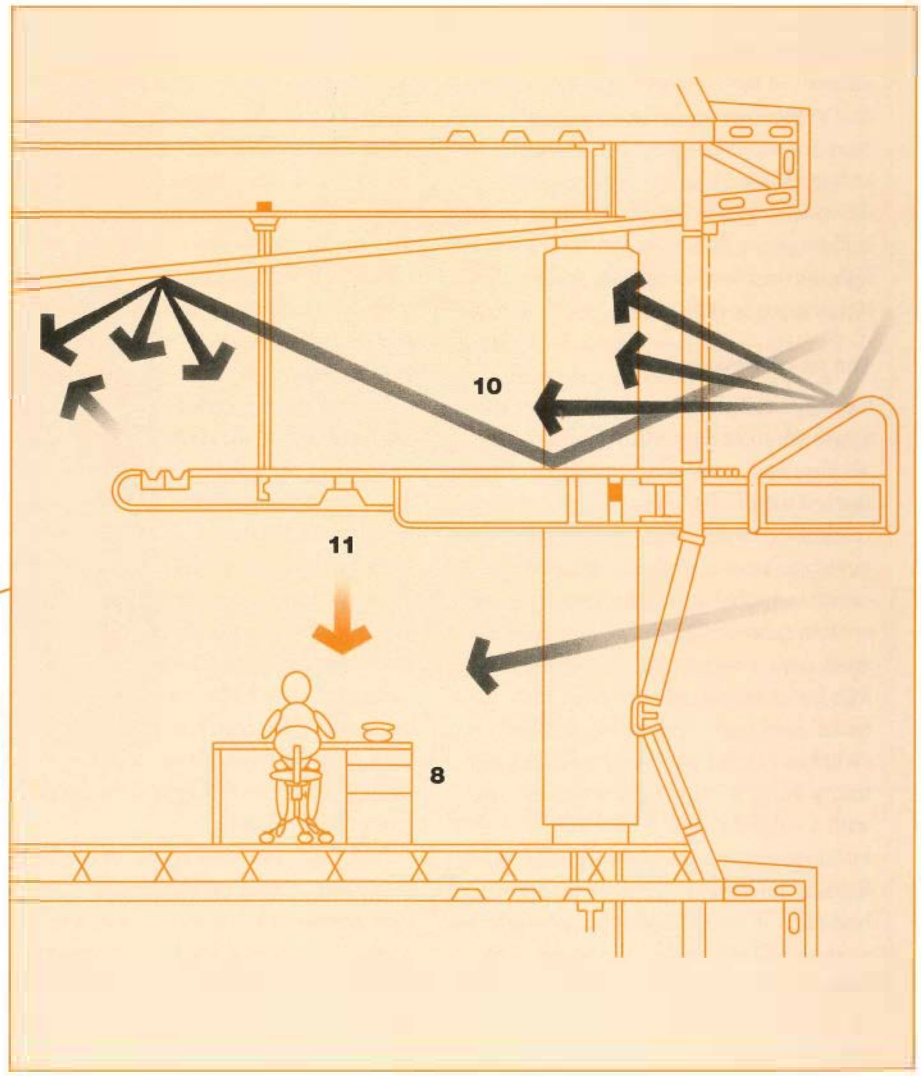
4 Photocells control electric lighting; as the amount of available daylight increases, electric lights are selectively dimmed. As daylight drops off, the electric lights brighten again.

5 Light shelves, structures which project both inside and outside a building, guide daylight into the interior while protecting outer offices from heat and glare.

6 Clear glass above the light shelves lets in as much light as possible; the light is diffused by the time it reaches building occupants.

7 Windows are plentiful and large.





8 Furnishings are important, too. Desks with light surfaces reflect rather than absorb light, adding to energy efficiency.

9 Solar control glass below the light shelves helps cut down on heat and glare in outer offices.

10 Daylight.

11 Electric light.

improved reflectors can recoup as much as 15% more light from a given lamp. Mirrorlike films made from substances such as Mylar, silver, and aluminum have been developed for NASA to deflect sunlight from spacecraft, and researchers at Lighting Technologies, Inc., are evaluating these and similar films on light fixtures as part of an EPRI project to see what benefits they can achieve.

Energy efficiency in lighting can also be improved by focusing light more directly on the work at hand. For example, standard fluorescent lamps tend to diffuse light evenly throughout a room, wasting much light on nonwork areas, such as walls and ceilings. By installing fixtures that guide light downward onto the task instead of out into the room at large, lower-wattage lamps may be used while personnel still get the same amount of light on their work. Fixtures that somewhat resemble egg crates have been installed in many commercial and industrial buildings to channel light down to where it is most needed. Other buildings are dimming general overhead lighting and installing task or directional lighting for specific work.

The on-off switch

Changes in lighting equipment are one approach to energy-efficient lighting; another approach is to turn lights selectively on and off through a variety of control systems, saving energy wherever possible. Years ago the only lighting controls available were ordinary on-off switches, according to Pertusiello, and most large pre-energy-shortage buildings lacked even those. It cost more to install hundreds of individual office switches than to pay the prevailing electricity bills, so buildings were designed with a single master switch for the entire building or for individual floors. When lighting bills went up, some changes had to be made, and individual switches were installed in many buildings. But even so, not everyone could be counted on to flip the switches off whenever possible.

The next development in lighting control was the on-off timer—a device set to turn lights on and off at preselected times. Because of their relatively high capital cost, these timers were installed in large, open office areas rather than in individual offices. The timer did its job without occupant input, but because offices were frequently occupied slightly before or after normal work hours, timers usually had to be set to allow extra time at either end of a lighting cycle for early-birds, stragglers, or cleaning personnel. This, of course, limited the efficiency of timing devices.

The extra-time problem prompted the introduction of occupancy sensors. These ultrasonic or infrared sensors, originally developed for building security systems, detect the presence of personnel in a given area and switch on the surrounding lights; when the area is vacated for a certain period of time, the lights are automatically cut. Occupancy sensors cost more than on-off timers and have only recently been available, so they are not yet widely used. They are typically installed in small commercial areas limited in the number of lights that any one person can activate by strolling down a hall.

Energy management systems (EMSs) are a still more advanced development in lighting control for larger commercial and industrial buildings. These computer-operated systems, available from a wide range of suppliers, oversee the energy use of an entire building—lighting, heating, ventilation, air conditioning, and other functions. Most major new buildings have EMS, and many existing buildings have retrofitted them as well. Choice of system computer depends on the size of the building and the level of complexity desired.

Building operators program the EMS computer to time all systems for the best energy efficiency possible, and this schedule can be altered as often as necessary. Pertusiello offers an example: if a meeting is scheduled for a particular conference room at 2 p.m., the EMS can time the HVAC system for that room to switch on at 1:30 p.m., the lights to go on at 1:50 when attendees are arriving, the HVAC to shut off half an hour before the meeting is scheduled to end, and the lights to go off half an hour after the meeting is over.

Light from outside

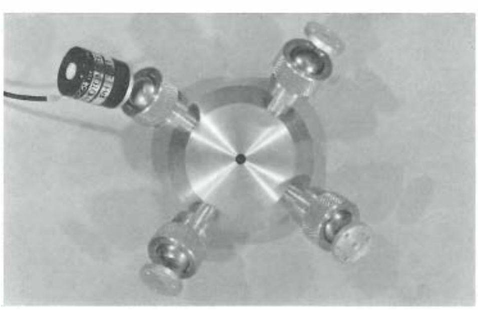
The latest word in energy-efficient lighting control strategies is a system that adjusts a building's electric lighting to match the brightening and dimming of the daylight outside so that electricity is relied on as little as possible: a daylighting system. Some industry observers estimate that perhaps 1000–2000 daylit commercial and industrial buildings have already been designed and constructed over the last five years in the United States, and many of these have toted up respectable energy savings.

Daylighting demands an elaborate lighting control system and an equally elaborate building design. The basic units of daylighting control are photocells, small photoelectric cells that are sensitive to daylight and are strategically positioned around the building's interior. Daylight that hits the photocell is converted to electric energy; the more the light, the greater the charge. When a predetermined amount of daylight reaches the cell, the charge triggers a mechanism that dims the building's electric lights accordingly. When the amount of daylight reaching the photocells drops off, the electric lights brighten again. Good daylighting systems are carefully designed so that indoor lighting levels are constant, even though daylight is continually fluctuating. Proper photocell placement, fixture location, lamp selection, and switching systems are all essential to daylighting success.

The design of a daylit building has to be just as meticulous as its lighting control system. Daylit buildings must be specially designed and built to collect as much daylight as required to light the interior, necessitating a radical departure from routine building design. Solid, There's more than one way to turn a light off to save electricity. The old on-off switch does the job, but the burden is on the individual user to do the actual switching. Timers take over that responsibility, but because they have to allow extra time at either end of the cycle to accommodate variances in use, energy savings are limited. Two newer developments are occupancy sensors and energy management systems (EMS). The ultrasonic or infrared sensors switch lights on when personnel are present, cut them when personnel leave. EMS are computerized systems that control lighting as well as heating, ventilating, and air conditioning. Photocells switch electric lights on when available daylight wanes and off again when daylight returns.


Photo courtesy FLEC Systems, Inc.

Photo courtesy General Electric Co.



boxlike buildings will not work; daylit buildings need large central atriums or projecting wings with which to capture light. Windows have to be abundant and tall to bring daylight into the innermost recesses of the building; projecting structures called light shelves usher light inside.

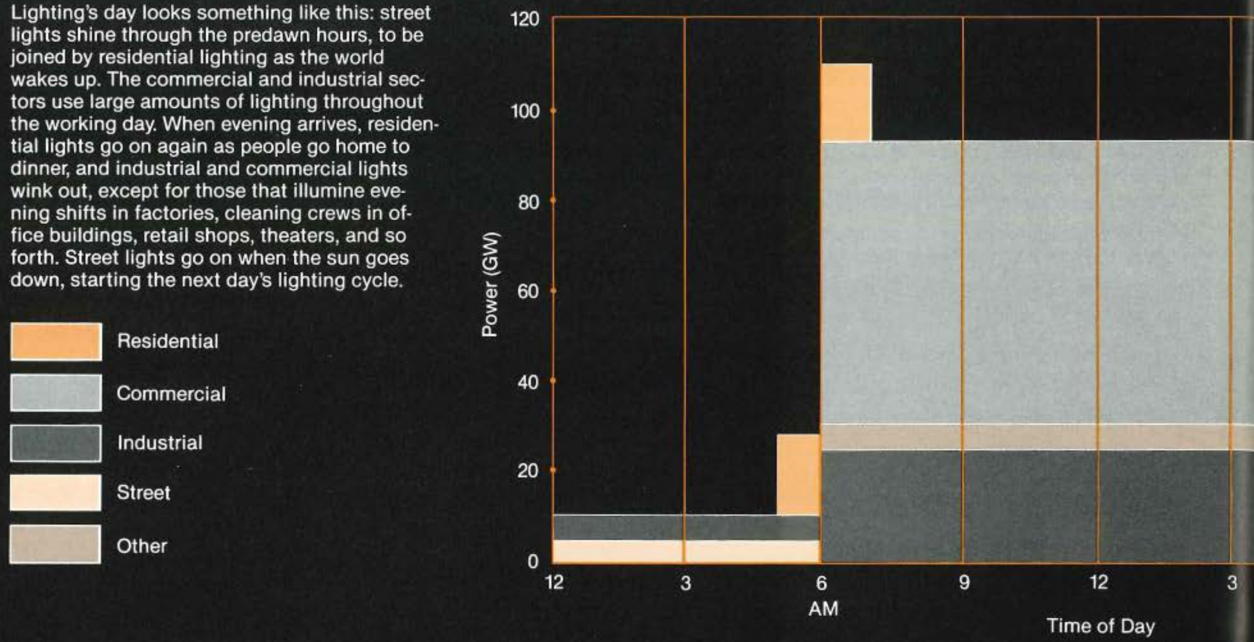
Proper design must also guard against too much light, which can cause undesirable heat and glare. The building itself can be oriented with maximum north-south exposures so that most of the light coming in is diffuse overhead light; minimum east-west exposures keep down direct glare and heat from the rising and setting sun. Specially tinted solar glass and reflective glass may also be deployed to filter out or deflect glare and heat. The building's HVAC system will have to be specifically designed to work with the heat that daylight brings in.

Daylighting systems are still being perfected and will be more widely used when design techniques become more readily available. These designs are a ticklish business because of the many systems to be considered and the many variables (such as local climate and immediate site conditions) to be factored in. Researchers are busily developing models to determine the best designs for given buildings, working with such aids as artificial skies that chart the effects of sun and clouds on daylight. EPRI, for example, has had a project with Lawrence Berkeley Laboratory under way for over a year to design guidelines for the selection and placement of photocells. As more becomes known about daylighting design, the relatively high initial cost of these buildings will drop, and more and more daylit buildings will be seen.

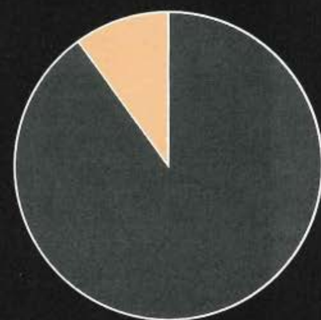
Bright—and efficient—future

Energy-efficient lighting choices are clearly available to all residential, commercial, and industrial customers; there are options for everyone in lamps and fixtures, control systems, and building design. But it may take a while before a 50% reduction in lighting energy con-

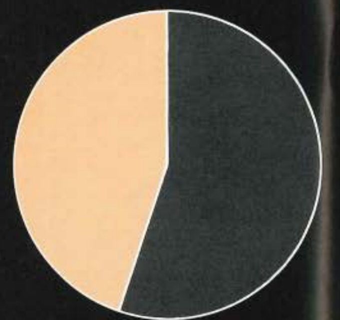
Lighting's day looks something like this: street lights shine through the predawn hours, to be joined by residential lighting as the world wakes up. The commercial and industrial sectors use large amounts of lighting throughout the working day. When evening arrives, residential lights go on again as people go home to dinner, and industrial and commercial lights wink out, except for those that illumine evening shifts in factories, cleaning crews in office buildings, retail shops, theaters, and so forth. Street lights go on when the sun goes down, starting the next day's lighting cycle.



The impact of lighting on electricity use varies widely, depending on what the lighting is used for. Still, lighting's share is never small. Most homes use about 10% of their electricity on lighting; the commercial sector spends 40–50% of its electricity on lighting, and much of this sector's cooling load is also indirectly attributable to lighting. The industrial sector expends anywhere from 10 to 20% of its electricity for light.

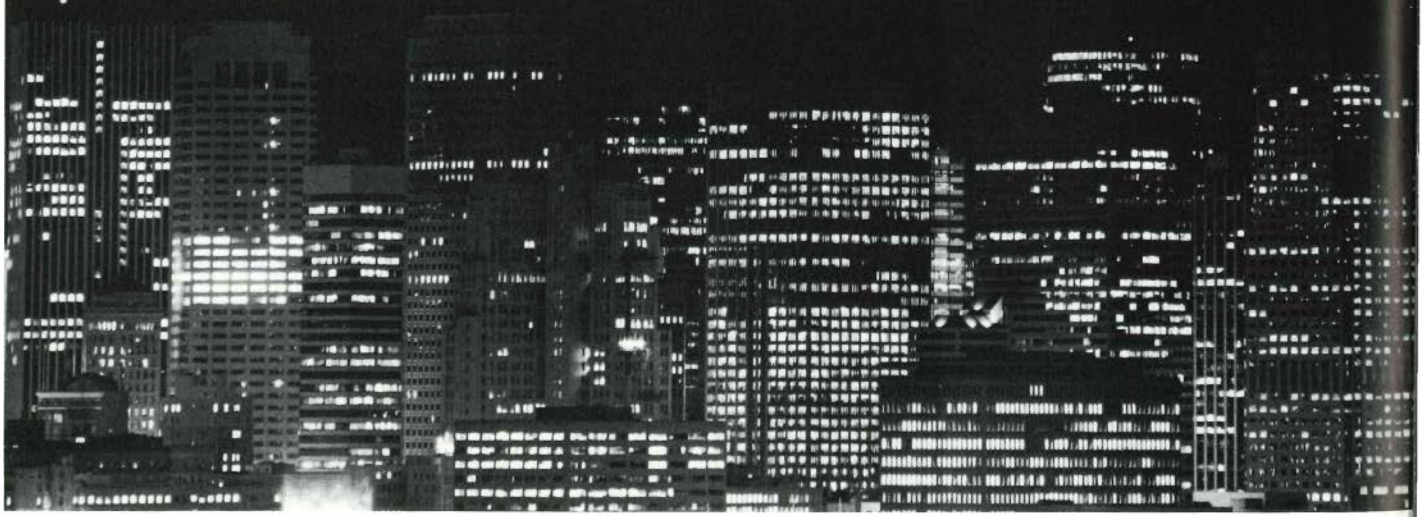


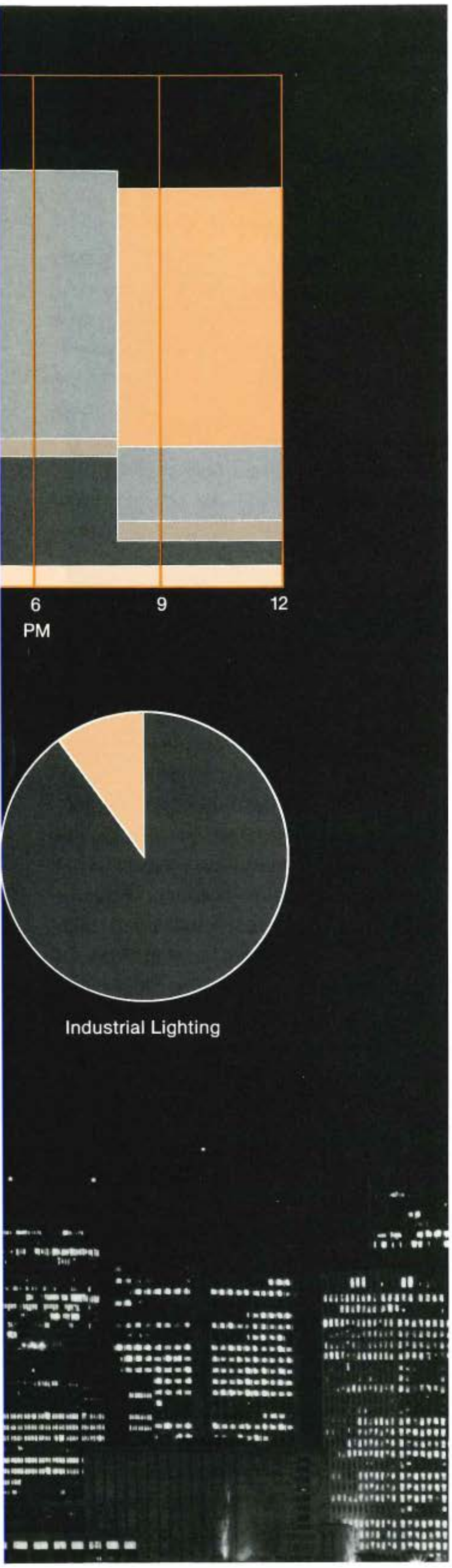
Residential Lighting



Commercial Lighting

Lighting's job is never done.





sumption can be achieved, cautions Pertusiello. Cost is the bottom line that governs how far people will go to conserve energy, and the cost of energy efficiency is not right for everyone.

In the residential sector, for example, lighting accounts for only about 10% of electric load, outranked by refrigerators, freezers, space heating, air conditioning, and water heating. Although a change in the lighting habits of all residential customers would make a significant difference in the total electricity that homeowners consume, the motivation for individual homeowners to save energy by buying energy-efficient incandescent lamps or installing fluorescent lamps amounts to only a few dollars or even cents a month. Moreover, the slightly higher initial cost of these options discourages many would-be converts to efficient lighting.

The commercial and industrial sectors consume far greater amounts of energy for lighting than the residential sector: lighting represents some 40–50% of commercial electric load and about 10–20% of industrial load. Because of this greater consumption and consequently higher electric bills, commercial and industrial customers are more amenable to adopting energy-efficient lighting. Many industrial and commercial customers have already conducted energy audits of their operations and put the resulting recommendations into action.

In the years ahead, energy-efficient lighting will likely become even more attractive to the commercial and industrial sectors. The nation's economy is inexorably changing from manufacturing to services, so the commercial sector, with its preponderance of paperwork, is growing. More and better lighting may be required to handle this shift. Lighting needs are changing in the industrial sector as well. Increased automation is reducing the need for high levels of lighting in certain industries, but an even stronger trend may be the shift from older industries like heavy manufacturing to newer, lighter industries like the manufacture of semiconductors and biomedical instruments. These newcomer industries involve precision assembly of minute parts, and lighting loads for the industrial sector as a whole are expected to grow as such industries proliferate, giving this sector additional incentives to make lighting more efficient.

Without question, much of the electricity used in lighting the offices, factories, stores, streets, and homes of the nation can be conserved. But it takes continued R&D and requires that the decision makers—everyone who uses lighting—know that they can save lighting energy without giving up adequate light. ■

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This article was written by Nadine Lihach. Technical background information was provided by Stephen Pertusiello, Energy Management and Utilization Division.

Decontaminating Reactor Coolant Systems

The LOMI chemical process quickly dissolves tough corrosion films that hold radioactive isotopes. Radiation fields on pipe surfaces can be cut by a factor of 20 before repair crews go to work.

Repairs in the coolant circuits of nuclear power reactors today can be done faster and cheaper than might have been expected, thanks to the advent of chemical agents and processes that reduce radioactivity levels where people must work. One particularly effective decontamination method, hinging on the action of low-oxidation-state metal ions (LOMI), was developed in research cosponsored by EPRI and the Central Electricity Generating Board (CEGB) of Great Britain.

The problem defined

Radioactivity outside the core of a reactor is found in corrosion films that incorporate activated species, mostly cobalt. Corrosion is inevitable, even in the purified, controlled water of a coolant system. And it is a continuing process as oxides are successively formed, either dissolved or spalled, and the products either precipitated or lodged at many points in the cooling water circuit.

Activation occurs in the reactor core, where scale formation is enhanced by the highest temperature in the circuit—just as at the bottom of a teakettle. Cobalt, being very easily activated, is the main source of migrant radioactivity. It results primarily from otherwise inconsequential corrosion of Inconel tubing in pressurized water reactors (PWRs) and the wear of valve seats and similar surfaces in boiling water reactors (BWRs), where it is an important constituent of hard-facing alloys.

Radiation fields resulting from this sequence account for nearly all the radiation exposure experienced today by workers in nuclear power plant inspection, maintenance, and repair. Expressed in man-rems, the total exposure in the U.S. power industry has increased four-fold in the past 10 years, from about 13,000 to about 52,000 man-rems annually; and the number of individuals receiving measurable doses has risen from 14,000 to more than 80,000 a year in the same period. About half the increased exposure results from the greater number of plants in operation, but the rest is traceable to higher radioactivity levels in plants and to longer cumulative maintenance times in the presence of radioactivity. Both the maintenance time and radioactivity have risen by about 50% and are reasonable targets for corrective action.

Early efforts are already showing results, the collective annual radiation dose leveling off in the last 2–3 years. Shrewd use of remotely manipulated equipment is partly responsible, as is special care in planning the sequence of maintenance tasks. But if doses are to be kept as low as reasonably achievable (the industry policy called ALARA), then it is also necessary to reduce radiation field intensities, especially in older plants.

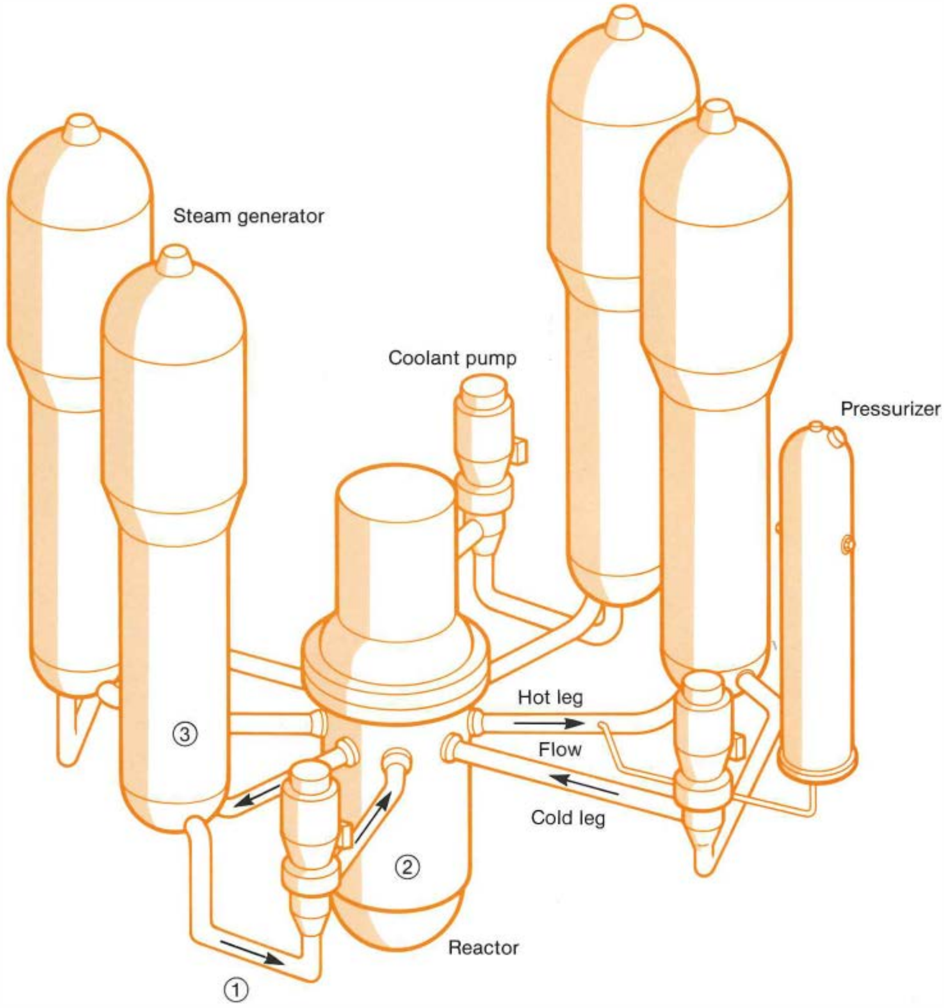
Chemical decontamination entails removing the radioactivity—at least, some fraction of it—by dissolving or dislodging the corrosion that fixes it on the inner surfaces of coolant valves and piping. Decontamination is rather like flushing a radiator: adding chemicals to the coolant, pumping it through the system, and then diverting it through an auxiliary external loop, where the corrosion wastes and their burden of radioactivity can be separated out.

Historically, corrosion products have been chemically removed with oxidizing agents (strong acids). But these entail the risk of further corrosion at the base metal surface. Reducing agents avoid that risk but are characteristically weak and slow to act, hence prohibitively expensive in extended downtime.

The LOMI chemical is a reducing agent, but with a difference. It contains an ingredient that changes the reactivity of iron, weakening the iron-oxygen bond so that oxides are more easily and quickly dissolved, thereby freeing the corrosion

Giving Dimension to the Problem

Miles of tubes and piping in the primary circuit (1) of a PWR are possible sites for very slow corrosion that releases ions of iron, cobalt, chromium, and nickel into the coolant water. Carried to the reactor core and temporarily deposited there (2), these corrosion products (especially cobalt) become radioactive. Later dislodged or dissolved and carried out into the coolant circuit again, activated products are incorporated into corrosion films (3), which thus become radioactive. Steam generator repair is made difficult by the presence of radioactivity inside the tubes. Replacement of recirculation piping in BWRs is similarly impeded.



products and any radioactive species for removal from the system.

Field-proven solution

Monticello, a 540-MW power plant near Minneapolis, Minnesota, owned and operated by Northern States Power Co., was the first operating plant in this country to use the LOMI process. The recirculation system of this BWR was decontaminated in March 1984 to clear the way for removal and replacement of the type-304 stainless steel piping that had suffered intergranular stress corrosion cracking (IGSCC). Quadrex Health Physics Systems, Inc., did the work, achieving a decontamination factor of 20—reducing radiation fields that initially ranged between 400 and 700 mR/h to about 21 mR/h.

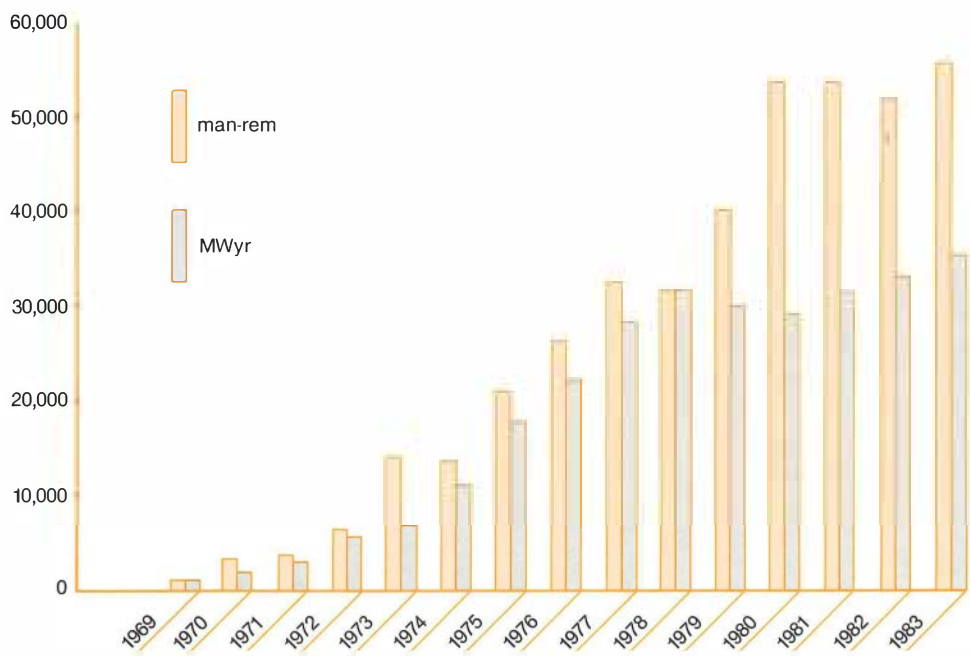
EPRI's Christopher Wood, one of the originators of the LOMI concept seven years ago, has closely followed its early application, scale-up, and transfer to the status of a fully commercial technology. Noting the U.S. and international radiation dose limit per person of 5 rem a year, Wood emphasizes that replacing the piping at Monticello without decontamination would have required several skilled workers for each one actually used. "Decontamination is important," he observes, "both as a matter of responsible personnel management and as a greater assurance of weld quality."

Gerald Neils, general manager of the headquarters nuclear group at Northern States Power, emphasizes that the LOMI decontamination did even better than expected. "We conservatively figured on reducing contamination activity by a factor of 5 and actually achieved a reduction in excess of 20. Our estimates indicate that the decontamination cut the total dose to people on the replacement work by about 800 man-rems."

Neils makes another point. "It takes three or four weeks' payroll investment just to train some of the people for critical work. Making it possible for a worker to spend more time on the job saves money."

Nuclear Energy and Radiation Trends
U.S. Nuclear Power Plants

Since 1969 the annual radiation dose to workers has increased faster than the generation of electricity at U.S. nuclear power plants. A sharp divergence in 1979 followed the Three Mile Island accident, when safety modifications were retrofitted in many plants and nuclear generation growth temporarily ceased. The trend in radiation dose began to flatten two years later with the advent of improved radiation control measures.



Decontamination is also an important need in PWRs. The problem there centers in the steam generator, the heat exchanger between primary and secondary fluid circuits. Crevice corrosion at the junction of pressurized-water tubes and their support plates creates an oxide buildup that progressively deforms (dents) and ultimately ruptures the tubes. As with BWRs, repairs require working in a radiation field.

Research origins

Chemical decontamination has made a very timely appearance on the nuclear power scene. Because its action in no way depends on the presence of radioactivity, it should also find use in other industries, especially if it speeds the dissolution of rust and corrosion without harm to base metal surfaces—which the LOMI process does.

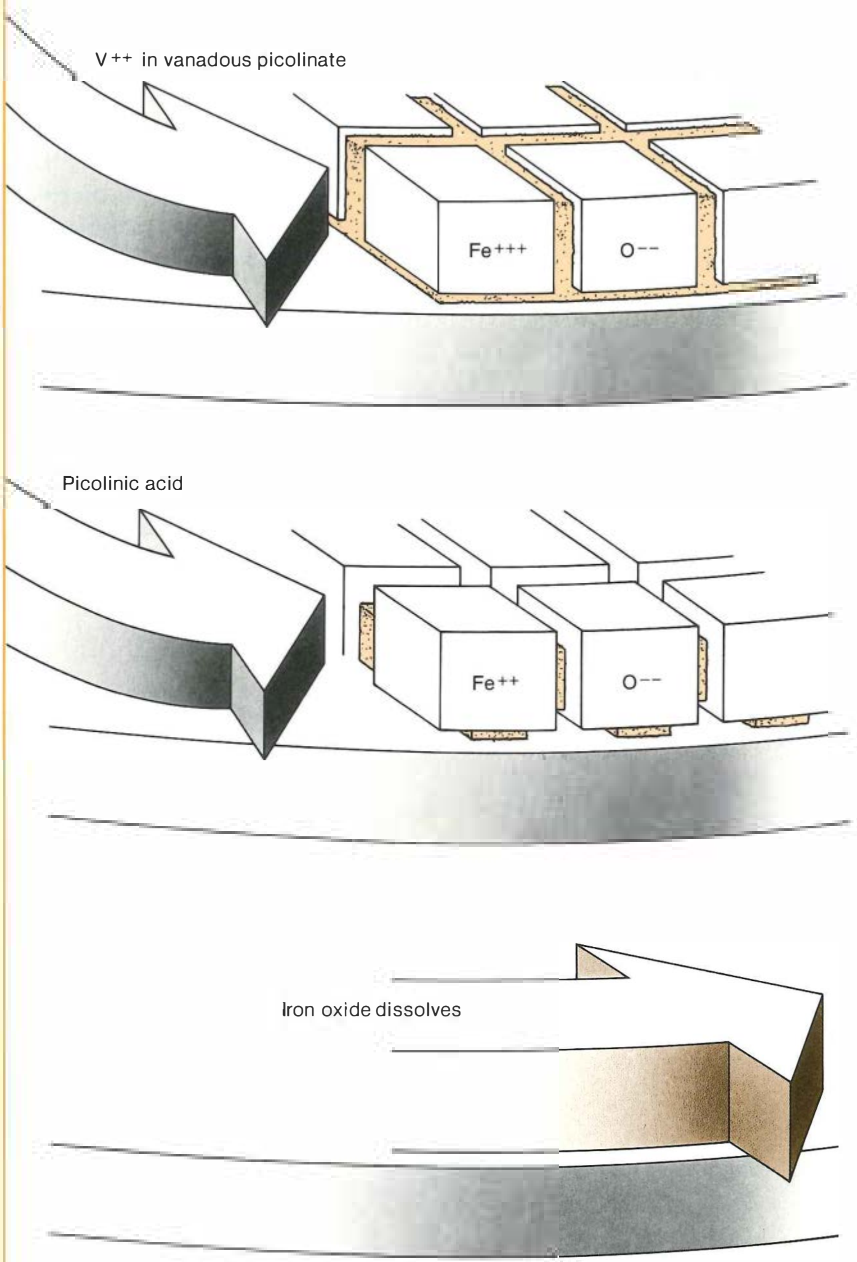
Why did chemical decontamination of the primary circuits of nuclear power plants become a research goal in 1977? And why was that goal established in Great Britain? At the time, all British commercial nuclear plants had gas-cooled reactors (GCRs), and these were susceptible to only about one-tenth the rate of radioactivity buildup in BWRs and PWRs.

Wood, who was then manager of the radiation chemistry section of CEGB's Berkeley Nuclear Laboratories, traces LOMI's origin to a pending CEGB policy recommendation that England adopt PWR technology for future nuclear power plants. In the course of comparative evaluation, the 1:10 disparity in GCR and PWR radiation levels was noted. Rather than upset labor practices, a strategy for reducing radiation potential was established for prospective PWRs. This motivated research into practical and economic means for doing it.

U.S. participation followed very shortly: Wood conferred with Robert Shaw of the Chemistry, Radiation, and Monitoring Program in EPRI's Nuclear Power Division. At that time Shaw was initiating research into radiation control technology for U.S. plants, including work on

Two-Step Reaction Sequence

Like the mortar between bricks, electron bonds hold iron and oxygen atoms together in the crystal lattice of a corrosion film. Those bonds are weakened by a spontaneous electron transfer from vanadium (in one of the LOMI process reagents) to iron (in the iron oxide). With the lattice thus disrupted, the iron oxide is easily dissolved by picolinic acid (the other reagent in the LOMI mixture).



THE LOMI CHEMICALS AT WORK

Crud is the traditional term for corrosion products deposited in a nuclear reactor core that become radioactive there. But the word has come to be more inclusive.

Today it also refers to activated particles that leave the core and are deposited in bends and recesses (so-called crud traps) elsewhere in the coolant circuit. And it applies to oxide buildup outside the core, where activated species precipitate after flowing in solution from the core.

Cobalt, although a minor product of wear and corrosion, is nevertheless the most important source of migrant radioactivity because it is so easily activated and produces long-lived and penetrating gamma rays. The main isotope is cobalt-60, which has a half-life of more than 5 years. In all cases, activation takes place at the reactor core, and primary coolant water is the transporting medium.

As a rule, EPRI's Christopher Wood notes wryly, "Crud follows Murphy's Law—deposits lodge where you can least tolerate them. Valves, where people must go to perform routine maintenance, have become the hottest spots in many plants. And corrosion films," he adds, "take up radioactive ions by chemical absorption. It's a physical process that involves chemical attraction and results in a film that can't easily be wiped off."

To break down these tough oxides, the LOMI chemicals act in two ways, first softening the film and then dissolving it. Both actions occur simultaneously in practice, as the required reagents are in the coolant water as a mixture.

The first action involves changing the oxidation state of the iron in the oxide—adding electrons to lower the ionic charge so that the iron becomes destabilized and readily soluble. A few elements are particularly effective sources of electrons (i.e., reducing agents) for this purpose.

Vanadium is one and is used in the LOMI process in the form of vanadous picolinate. Its oxidation state is denoted by II. When the reagent flows through the reactor coolant circuit, the vanadium (II) transfers valence electrons to the iron (III), reducing it to a low oxidation state and enabling it to be easily dissolved (the second action) in picolinic acid. The latter is a mild chelating agent; that is, it acts to keep the dissolved metals in solution.

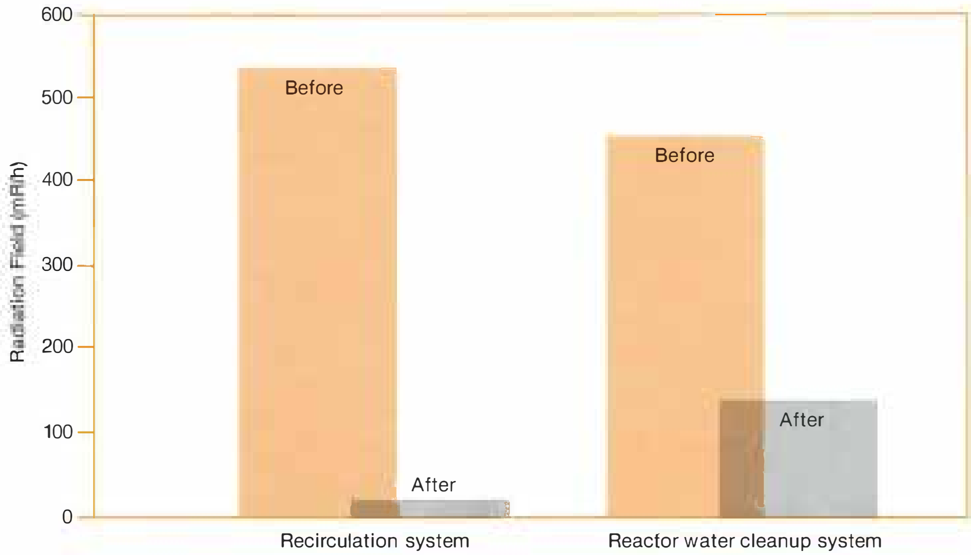
The LOMI process equipment consists of a skid-mounted array of pumps, heaters, and piping, together with tanks of reagent and drums of ion-exchange resin. Heaters maintain the process temperature at 80–90°C (176–195°F). Reagents are added to the coolant and pumped into the system in solution until they are removed by the ion-exchange resin in the cleanup phase of the process. Coolant and spent reagent from the system are passed through the resin, which retains the radioactivity.

Equipment to decontaminate the Monticello plant of Northern States Power in March of this year required 320 gallons (1.2 m^3) of concentrated LOMI chemicals—80 gallons (0.3 m^3) for each of two applications in each of two recirculation loops of that 540-MW reactor. About 12 hours were needed per application; together with other flushing procedures, the overall decontamination process took about 48 hours for each loop.

The capacity and character of the ion-exchange resins used to remove the waste are important. The more units of radioactivity that can be captured per drum, the fewer drums are needed (i.e., the less waste product to be disposed of). Also, the lower the concentration of chelating agent in the reagent, the better; its action would be undesirable in the waste product, which should remain as stable as possible in its final resting place, undisposed to react with its container or to leach away in the presence of groundwater. LOMI chemicals rate well on these points. □

LOMI Decontamination at Monticello

Radiation fields in the reactor recirculation system at Monticello were cut by an average factor of 20, but fields in the reactor water cleanup system (through which a portion of coolant is always circulated for chemical treatment) were cut by a factor of only 4. Because of the water temperature and oxygen content in the cleanup system, oxides there contain more chromium and thus are much more difficult to dissolve.



decontamination. "CEGB's ideas seemed speculative," Shaw recalls, "but the concept was exciting and it fitted in with our goals."

The outcome in 1978 was equally shared cosponsorship of a two-year project for fundamental investigation of corrosion product dissolution. Three criteria quickly emerged, which continue to be the indices for evaluating and comparing chemical decontamination processes.

- Decontamination factor (DF), the ratio of radiation field values before and after decontamination
- Potential of the decontaminant for corroding the base metal surface
- Volume of process waste, particularly that which contains activated (and other) corrosion products

The joint research, performed by Wood's colleagues at Berkeley Nuclear Laboratories, was indeed successful, and the LOMI reagents and prototype process equipment for their use were available ahead of schedule in 1980. The first application was at Winfrith, a 100-MW reactor and the only water-cooled power reactor in Great Britain. "It was a good test," Wood reports, "though it wasn't a really proper decontamination because we didn't have enough reagent. But it worked." In fact, the LOMI treatment was repeated at Winfrith in 1981 and has since become annual practice there.

Commercial introduction

LOMI technology moved to this country in 1982 with its use by Battelle, Pacific Northwest Laboratories to decontaminate portions of a steam generator taken from the Surry plant of Virginia Electric and Power Co. This steam generator was also the first PWR application of a process called Can-Decon, which Atomic Energy of Canada Ltd. originated and London Nuclear Ltd. marketed. Can-Decon preceded LOMI into large-scale use and was the only other process available until 1983.

Today, LOMI and Can-Decon are just two of several chemical decontamination processes being marketed. Wood reports that interest in LOMI has risen sharply in the past year. "Quadrex was licensed through CEGB late in 1982, Pacific Nuclear Systems & Services has since been licensed by EPRI, and three or four more U.S. firms have applied." For Wood himself, who joined Shaw's group at EPRI in March 1982, "The development of the process was exciting, but the real satisfaction has been to see it used in an operating plant like Monticello."

Even though the first trial at Winfrith

was nearly four years ago, Wood and Shaw consider LOMI still new in the commercial sense. The Battelle work in 1982 was its first U.S. contract use, and on that basis the LOMI process was entered in a 1983 competition among new technology developments, the annual IR-100 Awards, sponsored by *Research and Development* magazine. "It was a most welcome surprise to be among the 100 winners," says Wood, "and the publicity has been an undeniable benefit to our licensees."

Wood is thoughtful as he considers the reasoning behind LOMI's development and fast acceptance. "Utilities have to keep their workers' radiation dose as low as reasonably achievable, but at the same time they have to be concerned about using any chemical that could damage their plants." LOMI was specifically designed to be "forgiving": its reagents are essentially noncorrosive, so no corrosion inhibitors are required in connection with it. This is a further advantage, Wood claims, because inhibitors usually contain sulfur compounds that are second only to chlorides in their potential for contributing to stress corrosion cracking.

Action of the radiation field on the reagent is also a consideration, he notes. "If an inhibitor is broken down—destroyed in a radiation field—its end products could well be corrosive. LOMI reagents, on the contrary, are actually regenerated in a radiation field. Overall," he says, "our goal was to come up with fail-safe reagents that wouldn't cause problems if anything got out of control. The fact that the process is carried out at a subboiling temperature helps here."

Shaw reemphasizes the business aspect of the development. "Radioactivity is the phenomenon we're dealing with, of course, but the problem we're focusing on is cost, not safety—exposure limits are complied with in any event." Radioactivity is easily and accurately measured, he points out, so it poses no surprises; it is avoidable and not a worrisome hazard.

The cost of that avoidance is something else, however, in the ramifications of finding and training enough workers to perform repair tasks in and around contaminated components without exceeding individual radiation dose limits. Echoing the comment by Neils of Northern States Power, Shaw points out that it is expensive to hire "jumpers" (those who can perform only one brief portion of a task during the year). "And," says Shaw, "here is where safety ultimately can be an issue. Not just the worker's health, but the reliability and quality of the work done under such specific time pressure."

Clearly, the recent LOMI decontamination by Quadrex at Monticello is high on Shaw's and Wood's minds. But Wood foresees that decontamination will soon move out of the category of a special repair chore and become a routine maintenance procedure at U.S. plants. "Our new goal is to demonstrate that the entire coolant circuit, including the fuel, can be decontaminated immediately after a shutdown."

Wood sees two benefits: shorter downtime and slower recontamination after a plant returns to service. He points out that whole-core decontamination has been successfully done at Canada's Candu reactors (with the Can-Decon process) and at Winfrith (most recently with the LOMI process). "Who knows," he suggests, "with what we're learning about how to control radiation buildup, we may be able to keep the fields in an old plant really low, once it's been cleaned up." ■

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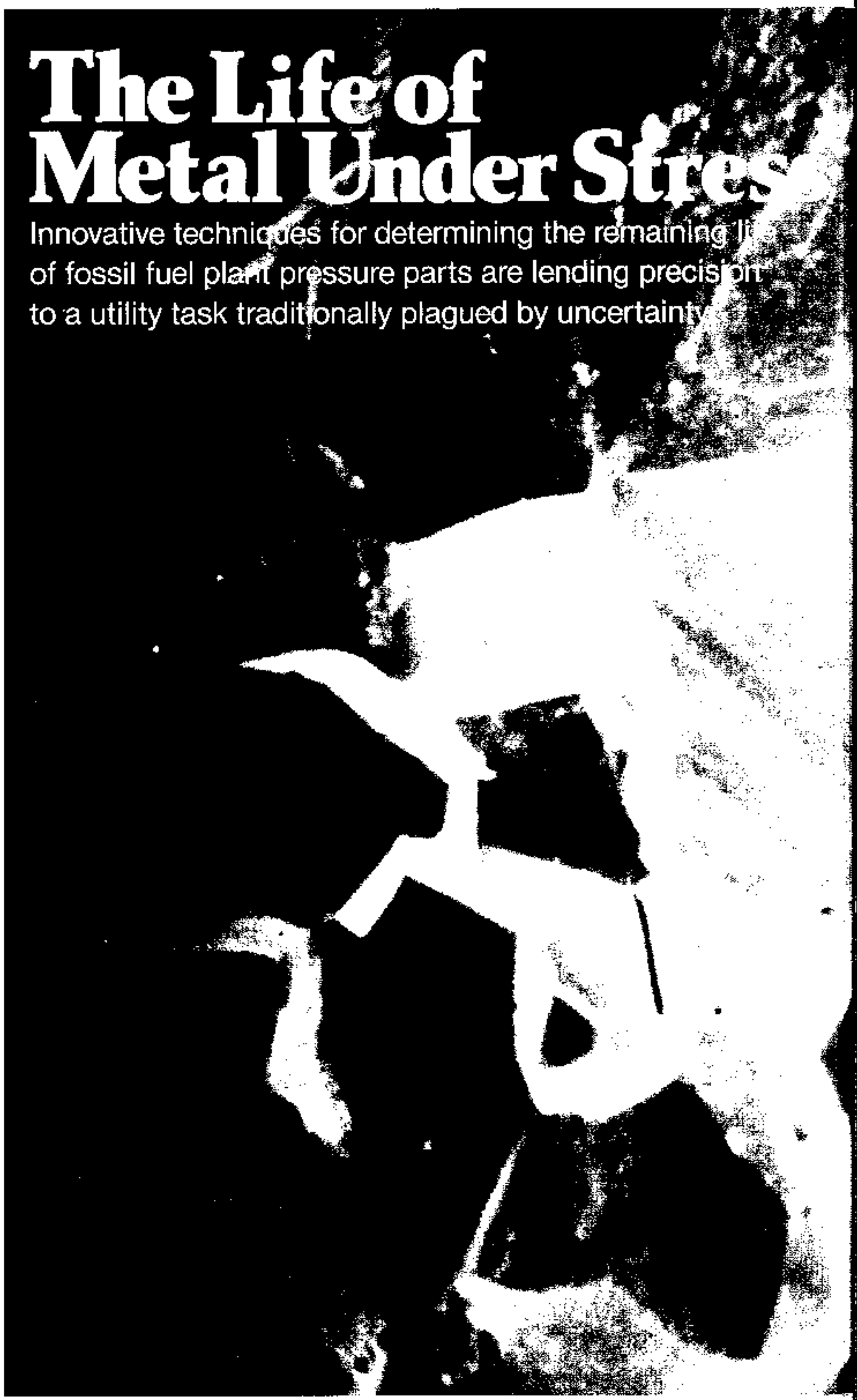
This article was written by Ralph Whitaker. Technical background information was furnished by Christopher Wood, Nuclear Power Division.

The Life of Metal Under Stres

Innovative techniques for determining the remaining li of fossil fuel plant pressure parts are lending precision to a utility task traditionally plagued by uncertaint



Pressure parts of a fossil fuel power plant boiler—pipes, tubes, headers, and drums—are designed to withstand varying extremes of heat and force over prolonged use. Eventually, however, the cumulative effect of applied stress and temperature takes its toll; parts either wear out and must be replaced, or they fail while operating, taking an entire generating unit out of service. Approximately half of all forced outages among fossil fuel plant boilers result from failure of pressure parts.

Determining when a boiler pressure part is about to fail is part science, part educated guesswork today. Identical parts manufactured to the same specifications will show widely different service terms, depending on their individual material properties and histories of stress loading.

Current utility industry practice involves estimating a component's remaining life on the basis of its stress and temperature history, as well as data obtained in destructive rupture tests of large metal samples. But this approach is costly, limited in application, and fraught with uncertainty in the interpretation of results.

Knowing a part's remaining service life is critical for plant reliability, but it is also a concern of increasing importance to utilities seeking to defer new plant construction. The industry trend toward extending, wherever possible, the service life of existing plants beyond their original design is creating demand for more quantitative and accurate techniques for estimating the remaining life of boiler pressure parts, as well as that of other key components.

EPRI is supporting the development of several nondestructive techniques for pressure part life assessment. In addition, a methodology for combining the results of these techniques with data from plant operating history promises to become a useful new tool not only for estimating remaining life but also for identifying the causes of—and remedies for—pressure part failure. Eventually, researchers believe, some of these tools will be incorporated in simple-to-use computer programs with which utilities can routinely determine whether a pressure part should be replaced or can remain in service.

The nature of metal stress

Strain accumulates in the microstructure of metals when they are subjected to high temperature, pressure, and other stresses over time. In the early stages of strain, damage begins to appear as minute cavities at the grain boundaries. With increasing strain, the cavities become more oriented along the grain boundaries, eventually linking up to form microcracks, which, in turn, lead to macrocracks—the last stage prior to full fracture.

According to Ramaswamy Viswanathan, manager of mechanical metallurgy projects on EPRI's R&D Materials Support staff, "Two general types of structural damage result from mechanical stress in metals at elevated temperatures: creep and fatigue, the former being mainly time-dependent and the latter largely cycle-dependent."

Creep occurs over time when metal is under steady stress and temperature, explains Viswanathan. Fatigue results when metal undergoes changing thermal stresses, such as those that occur in pressure parts of a steam-electric generating plant where temperatures can vary from ambient to 1000°F (537°C). In general, stress from fatigue occurs less in pressure parts of a baseload plant than in those of an intermediate or cycling plant that frequently goes from shutdown or minimum load to full load.

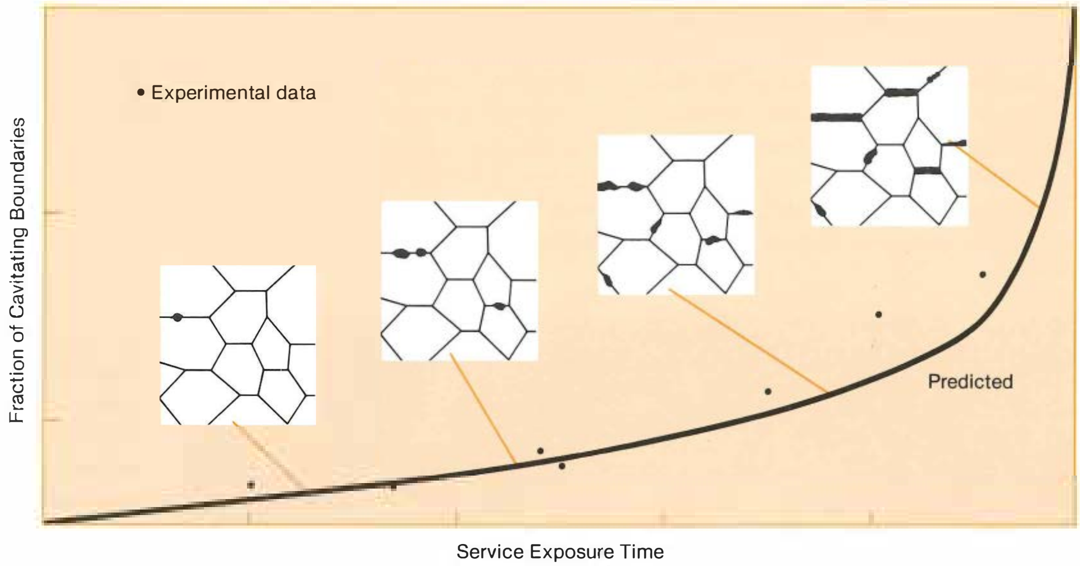
Depending on the specific boiler pressure part, its operating temperature range, and the plant operating history, creep or fatigue may dominate as the type of strain that most frequently leads to failure. Often, however, both play a role in weakening the metallic microstructure. Knowing which class of strain is dominant in a particular pressure part can be critical in choosing a corrective or preventive strategy, such as replacing a part with one made of a more creep-resistant alloy or more conservative cycling of the plant to minimize fatigue damage.

"Most boiler components in a baseload plant experience mainly creep damage in the first 10–20 years of life because the plant, being among a utility's most efficient generating units, is usually run at full load," notes John Dimmer, project manager for boilers and related auxiliaries in the Coal Combustion Systems Division. "As the plant grows older and less efficient, it is run more as an intermediate or cycling unit and the fatigue component of stress increases."

Boiler pressure parts include both thick-walled and thin-walled components. Thick-walled components are typically the main steam line piping, drums, and headers. Thin-walled components of interest are the superheater (SH) and reheater (RH) tubes.

Failure of the SH/RH tubes is a major, frequent cause of forced outages of boilers. Such failures are costly; a single tube failure in a 500-MW boiler can mean as much as $750,000 to a utility in fuel transfer costs alone, assuming it takes the average three days to make the repair.

In addition to tube rupture from creep damage after years of service, a common failure mode results from a combination



APPROACHES TO REMAINING-LIFE ASSESSMENT

Calculation

- Remaining life is determined indirectly by calculation of expended life on the basis of operating history and monitoring.
- Large uncertainties in temperature, stress, cycles, and materials properties lead to large errors.
- In-service degradation of materials is not taken into account.
- Crack initiation is used as a failure criterion.

Direct Post-Service Evaluation

- Remaining life is determined directly.
- Knowledge of prior service history is not essential.
- Data scatter in materials properties is not a concern.
- In-service degradation of properties can be accounted for.
- The method yields a significantly more accurate estimate of remaining life than calculation-based procedures yield.

Destructive Methods

- Procedures involve destructive evaluation of large samples.
- Procedures must be preceded by nondestructive inspection to identify sample locations.
- Frequently it is not possible to remove large samples.
- Procedures are expensive and time-consuming.
- Destructive methods are not a monitoring technique.
- Procedures may involve extended plant outage.

Nondestructive Methods

- Procedures include miniature metallographic samples, plastic replication, strain monitoring, and other, more-conventional inspection techniques (such as eddy-current monitoring, die-penetrant, ultrasonic detection, magnetic particle inspection) for early warning of damage.
- Surface replication can detect minute cavities that are the earliest signs of damage.
- Information gathered with nondestructive methods can be combined with standard crack-growth data for accurate estimates of remaining life.
- Periodic monitoring is possible.
- Procedures are less expensive and time-consuming than destructive tests.
- Nondestructive methods are more accurate than calculation-based methods.

Evolution of creep damage is categorized by the number of cavities that form along metal grain boundaries with increasing service exposure. Damage begins as isolated cavities; with increasing strain, the cavities grow more numerous and become oriented along the boundaries, eventually linking up to form microcracks. Further strain leads to macrocracks, at which point the metal component is considered to have failed and requires immediate repair or replacement. Data points obtained in limited experimental creep rupture tests show good agreement with predicted values represented by the curve. If additional data validate this preliminary model, local creep strain in a component—and hence its remaining life—can be more accurately estimated.

Key features of the principal approaches to estimating remaining life of pressure parts are indicated in this overview. A preferred approach combines calculation-based methods with nondestructive post-service examination. Standard calculations are used to determine when and where to inspect for damage. Then, direct nondestructive evaluation, crack-growth information for degraded material, and fracture mechanics are used to estimate further inspection intervals and remaining service life.

of creep and fatigue at the point where tube sections made from different steel alloys are welded together. These dissimilar metal welds (DMW) frequently fail from creep and fatigue because the alloys have different rates of thermal expansion.

The problem is reported worldwide by utilities. In the United States a survey conducted by a task force representing industry association technical committees found that slightly more than a third of the 54 utilities questioned have experienced DMW tube failures. The problem was found to be prevalent in about a fifth of the 320 generating units studied.

Drums, headers, and steam pipes fail much less frequently. But because of their strategic importance to plant operation, such parts are of even greater concern with respect to plant life extension. Thick-walled pressure parts require long lead times for manufacture and an extensive plant outage for replacement. Moreover, the operating environment of these components is often outside design limits, and because of overheating, many headers will require replacement well before they reach design life. Under these conditions, creep is the primary damage mechanism.

Current practice falls short

Two basic approaches are used in the industry today to predict remaining creep life of pressure parts. One involves evaluating the operating stress and temperature history of a component in conjunction with standard material properties data. The other approach is to examine and test samples taken directly from a suspect location in a component.

The first approach is predicated on the so-called life fraction rule, which, in layman's terms, says that the fraction of a component's service life that has been expended, plus the fraction of life remaining, equals 1. Thus, if expended life can be estimated on the basis of knowledge of the stress loading history, the remaining life fraction is a straightforward calculation. In practice, however, significant uncertainties undermine confidence in the numerical results.

Volumes of standard material properties data, including creep rupture limits, are published for nearly every metal and alloy made. Yet these data have significant scatter bands of uncertainty because of variability that results in the steelmaking process from one batch of metal to the next. Moreover, because of a lack of long-term creep rupture test data, results of short-term tests have to be extrapolated to predict material behavior under operational conditions.

Other factors, such as the effects of steam-side oxidation and (in the case of SH/RH tubes) fire-side corrosion, further blur the apparent quantitative precision in relating the published standards to a component's stress history. Such concerns, plus questions about the validity of the life fraction rule itself, make this approach, at best, useful for identifying parts that should be periodically inspected during their service life.

Rupture tests of actual metal samples provide a more confident means of determining remaining useful life. The tests are accelerated by conducting them at temperatures much higher than the component would experience in service. Results are plotted as time-to-rupture against temperature and then extrapolated to the service temperature range. Because the results relate specifically to the affected component, the data scatter band of uncertainty associated with the variability of virgin metal is not an issue. Knowledge of the part's operating history is no longer essential.

Creep rupture tests involve costly removal and destruction of large metal specimens, however, making this approach unacceptable for periodic assessment of a component's remaining life. An ideal life assessment technique would involve nondestructive testing and permit regular, inexpensive evaluations with few limits on the number or type of locations that could be examined. Development of tools that can form the basis of such an approach has been the focus of EPRI's efforts in this area.

When EPRI's work in pressure part life assessment began in 1982, there were no completely nondestructive techniques available that could detect the early stages of cavitation and crack nucleation in components. An initial goal was to develop techniques for microscopic examination and testing of small samples removed from a component. Since then, however, significant success has been achieved in assessing surface damage in headers with a nondestructive technique that uses cellulose tape to make a replica of the metal surface microstructure for later analysis.

In Europe, where plant life extension has been of longstanding concern among utilities, organizations such as the Central Electricity Generating Board (CEGB) of England and Rheinisch Westfälischer Technischer Überwachung Verein (RWTÜV, a firm based in Rhine-Westphalia, West Germany, specializing in technical monitoring) have been particularly active in developing tools for component life assessment. EPRI is working with CEGB to transfer to the United States some of the expertise already developed.

CEGB has proposed a procedure for applying standard creep tests on millimeter-scale miniature specimens of metal that can be taken from the critical location in a component; this technique complements metallographic examination with a scanning electron microscope of samples in the size range of about a centimeter. The samples required with both techniques are small enough to consider the methods nondestructive.

CEGB and Combustion Engineering, Inc. (C–E), EPRI's domestic contractor on the project, are now taking boiler header specimens from plants in both the United States and the United Kingdom with the aim of combining the sampling and testing methods. The work, expected to be completed within three years, could lead to similar procedures applicable to high-temperature, non-pressure-part components, such as rotors and casings.

Weld failure analysis

DMWs are widely used to join ferritic steel to austenitic steel. Austenitic or nickel-alloyed steel is preferred in the high-temperature, high-pressure SH/RH finishing stages for its increased creep strength and resistance to oxidation. Less expensive, low-alloy ferritic steels are used in tubing for sections in the SH/RH area where temperatures are less severe. Very simply, when metals having different thermal expansion characteristics are welded together, creep and fatigue stresses tend to concentrate in the heat-affected weld zone and lead to eventual failure. Improved welds, accelerated tests to evaluate weld performance, and field methods to assess the remaining life of welds are important R&D objectives.

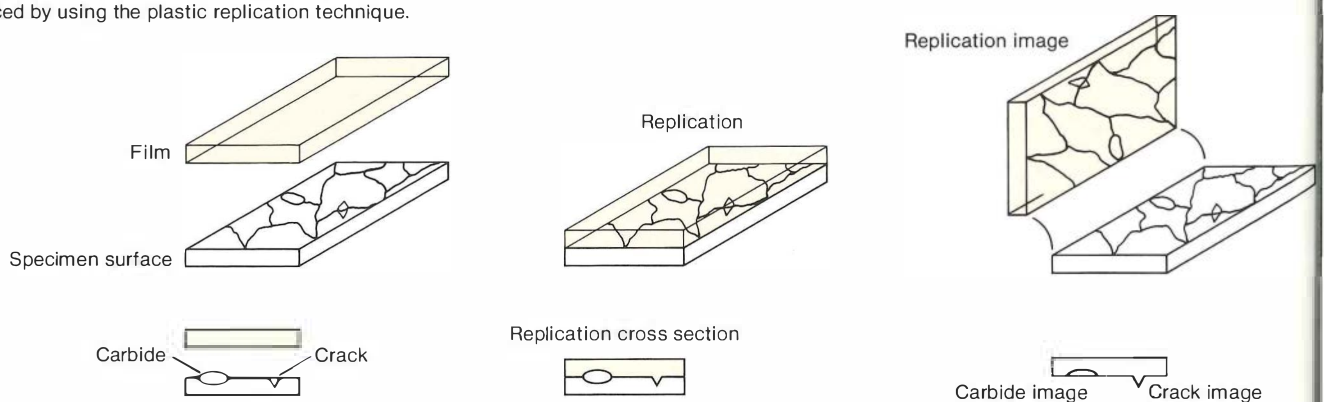
Intensive and systematic R&D efforts by EPRI in the last few years have resulted in major steps toward all these objectives. Metallurgical and engineering analysis of long-term service samples from operating plants have identified the boundaries of excessive system load and temperature that are the principal causes of premature DMW failure in baseload power plants. Metallurgical changes and stresses that result from differential thermal expansion have been explained; operating conditions under which DMWs made with stainless steel filler can perform satisfactorily in baseload plants have also been identified.

Service conditions that require use of nickel-based weld filler metals can now be determined. These fillers show significant improvement in service life over stainless filler weld metal in plants operated as cycling units, where the need for lower differential thermal expansion at DMW locations is an important factor. In addition, a realistic and highly accelerated (100×) laboratory test has been developed for ranking a weld's service performance. Further performance gains are anticipated from improved filler metal compositions and weld designs.

Damage prediction

One important product emerging from the extensive field inspections and metallographic examinations sponsored by EPRI is a procedure that enables calcula-

Microstructural surface details in metal are faithfully replicated on softened cellulose acetate film. After it dries and hardens, the film is peeled off and mounted on a glass slide for later laboratory analysis. Comparison of a replicated microstructure with that of an actual metal sample confirms that any feature detectable in a metallographic specimen can be reproduced by using the plastic replication technique.



tion of the total damage to a DMW from steady-state and cyclic loads on the basis of a knowledge of the weld's loading history. Called PODIS (prediction of damage in service), the procedure is expected to become a useful empirical tool not only for estimating remaining life but also (more important) for identifying the root cause of DMW failures so that appropriate remedial action can help avoid recurrence of the problem.

With the PODIS procedure, a weld's loading history is defined in terms of time, weld metal temperature, change in weld metal temperature, the number of cycles of temperature change, axial stress at the weld from pressure, dead weight, and restrained thermal expansion loads within the tube assembly. These data are gathered from plant records, design drawings, and overall inspection of the boiler. The procedure was developed by the Metals Properties Council and General Atomic Co. under EPRI contract.

PODIS assumes that a theoretical estimate of damage may be obtained by linear addition of three components of damage derived from the loading history. These components correspond, in a simplistic sense, to damage resulting from cyclic stress relaxation, steady-state creep, and fatigue. The magnitudes of damage for each category are calculated from empirically derived data from service samples and laboratory samples with known stress histories. Linear addition of the components gives a value of total damage, with a total value of 1 corresponding to a through-wall fracture of the DMW.

Viswanathan cautions that the assumed linear, additive relationship between creep and fatigue has not been demonstrated. Adds Viswanathan, "It could turn out, as we learn more, that there is a synergistic effect between the different components of damage and that the actual relationship between damage and stress is much more complex."

Using PODIS, predictions of total damage at a weld have been made in a limited number of cases on the basis of knowledge of a weld's test or service history. The actual extent of damage was then determined in terms of the fraction of wall thickness that was cracked from metallographic sections of the DMW samples. "Agreement between the predicted levels of damage and the actual observed damage has been good," notes Viswanathan.

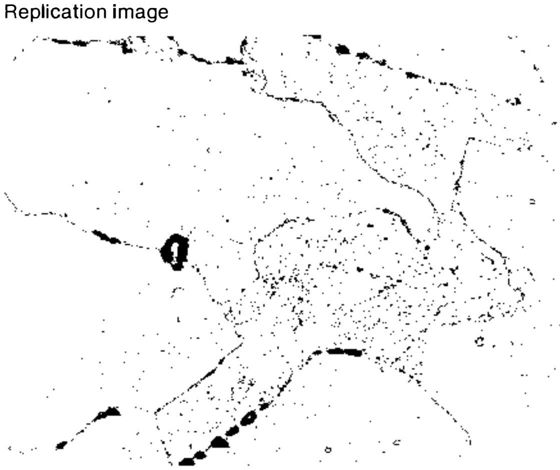
Though still in a preliminary stage of development, PODIS could eventually serve as a means of differentiating types of damage to identify the origins of stress. For example, a large indicated value of creep damage would suggest excessive stress from support malfunctions, tube sagging, and other causes or from excessive temperatures. Alternatively, a large value of stress relaxation–type damage would suggest relocating a DMW to eliminate constraints to thermal expansion.

Two cases of successful application of the damage assessment methodology are the River Rouge Unit 3 of Detroit Edison Co. and the Tennessee Valley Authority's Cumberland Unit 2. At the River Rouge unit, miniature wedge samples of welds were extracted and examined at high magnification (500×) in the laboratory. At the TVA plant, tubes containing welds were removed and examined. Detailed stress analyses of the critical locations were performed. On the basis of the data gathered, it was concluded that considerable service life remained in the DMWs at both plants and that replacement work is not needed for several years.

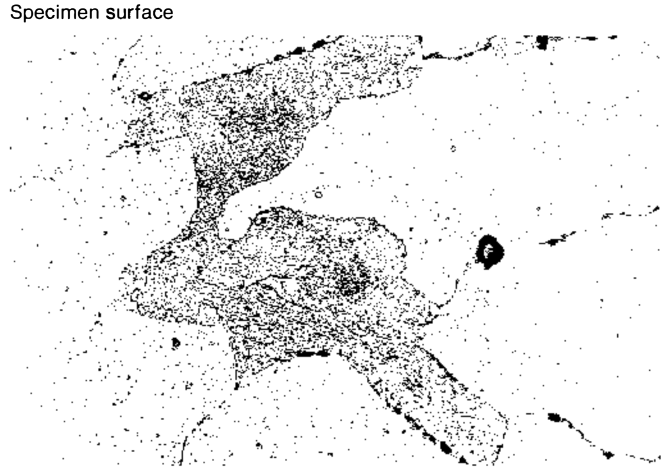
"We are optimistic about the potential of PODIS as an effective tool for determining failure causes, pinpointing remedial measures, and estimating remaining life of DMWs," says Dimmer. He points out, however, that field application of PODIS has been primarily with stainless steel filler welds. "As we expand our data base to include more studies of DMWs with both nickel and stainless filler welds, our confidence in its application will improve."

In subsequent phases of R&D on DMW failure, the PODIS procedure will be refined and applied at seven additional plants. The broader spectrum of weld loading and plant operational histories will be correlated with results

Replication image



Specimen surface



from metallographic and nondestructive tests, including some not yet fully developed, such as X-ray and acoustic emission techniques.

In the meantime, investigations are under way on improved weld filler metals and weld designs that are expected to add significantly to service life. An anticipated result of all this work will be two manuals for plant engineers on DMWs—one for weld damage assessment and another for improved weld design and procedures.

Surface replication

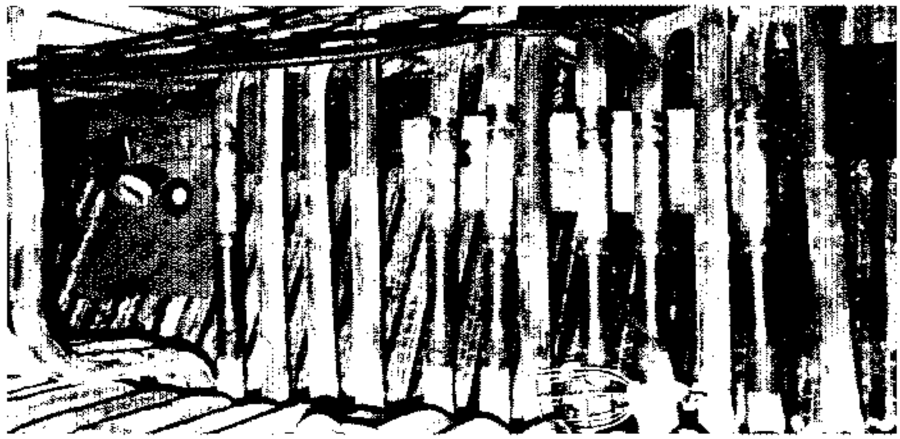
Current nondestructive evaluation techniques are unable to detect the minute cavities in the metallic microstructure that are a prelude to microcracking of high-temperature, heavy-wall piping in baseload plants. If the evolution of this microscopic damage could be quantified in terms of operational parameters, such as time and temperature, the component's remaining life could be estimated with reasonable accuracy on the basis of metallographic characterization of the current level of damage.

A qualitative procedure advocated by RWTUV treats damage as various classes (ranging progressively from isolated cavities to oriented cavities to microcracks as the cavities link, leading to macrocracks), each of which calls for different specific action. In the absence of a well-defined quantitative relationship between damage evolution and operating parameters, however, the procedure leads to conservative conclusions. EPRI's work in the field to develop quantitative damage models is expected to help make this approach a more precise tool for life assessment.

In the interim, a technique for replicating the surface microstructure of metal has become available for inspecting creep damage in heavy-wall pipes. The technique, used by some European utilities for metal inspection, has been recently demonstrated in utility application in the United States through EPRI's projects.

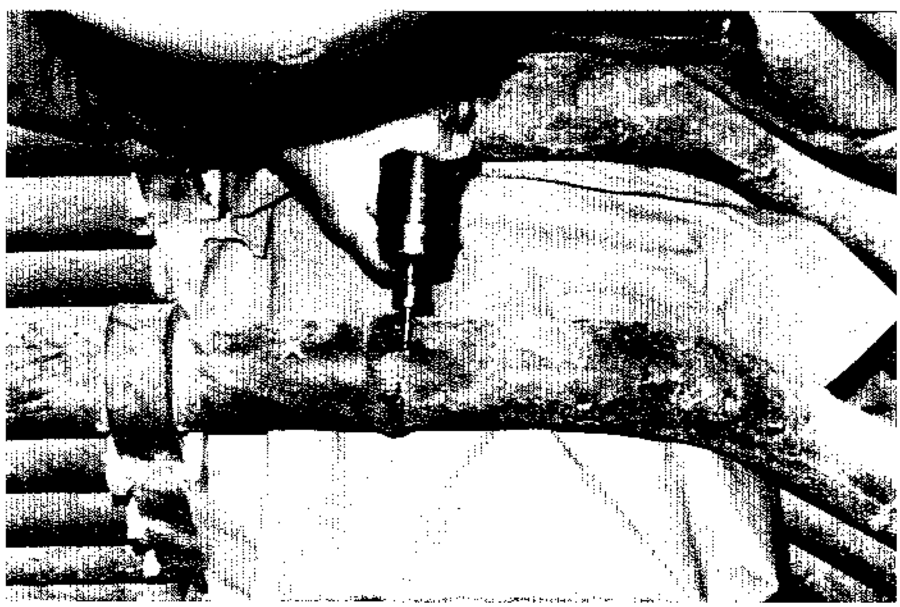
The basic procedure of the replica technique is to apply a cellulose acetate tape

Creep and fatigue damage tend to concentrate at superheater/reheater tube welds because dissimilar alloys react differently to thermal stresses.



The inspection area on a pipe weld is ground and polished in preparation for surface replication with cellulose tape.

Extraction of a metallographic boat sample from a superheater tube dissimilar metal weld; the centimeter-scale sample is examined later in a laboratory.



to a pipe's outer diameter surface after it has been ground, polished, and etched, using standard procedures. The tape—2 mils thick and softened with a methyl acetate solvent—is allowed to dry on the metal surface and is then removed, mounted on a glass slide, and stored.

In this condition, the tape faithfully reproduces all the microstructural details contained in the metal. The tape can then be examined in the laboratory with a scanning electron microscope; observed damage can be characterized with a degree of resolution not possible by field metallography.

C–E, working under EPRI contract, has applied the technique at several utility sites. The first involved the inlet tee on a header that had operated for approximately 28 years and was known to have undergone several prolonged temperature excursions. A section of the tee was removed from service because of visible cracks in the outer diameter surface. The sample provided an opportunity to directly compare the replicated structure with the actual structure from large samples prepared under laboratory conditions. The results confirmed the technique's ability to detect the early stages of creep cavitation; they indicate that any structural feature that can be resolved in a metallographic mount by using a light-optical microscope can be reproduced on a replica.

In another successful replication, type-316 stainless steel steam line piping was evaluated. One section had developed extensive stress rupture cracks, requiring an investigation of the full run of the steam line for evidence of incipient creep-rupture damage. The replica technique allowed the piping to be evaluated in place. Those sections in which cracking and cavitation had begun to develop were identified and replaced.

Similar analyses have been completed at six other generating stations; in four of the units examined, immediate corrective actions were required. Thanks to detection with surface replicas, the possibility of unanticipated outage from creep damage at these units has been eliminated. In the other units, early warning of incipient damage prompted more frequent inspections to monitor cavity progression.

Nondestructive and inexpensive, the plastic replication technique offers several other advantages. It is applicable to many components, materials, and material conditions, permitting detection and monitoring of creep damage from its earliest stages. Very high resolution of mounted replicas can be achieved with a scanning electron microscope. The technique can also be used to detect damage in localized regions, such as heat-affected zones of welds.

The surface replication technique also has potential application for monitoring the microstructure of metals in nuclear components, gas turbine blades, and other plant components where direct metal sampling is difficult.

The principal drawback of surface replication is that the technique is confined to the outer diameter of a component. It is thus unsuitable for application to SH/RH tubes or to DMWs because damage in these areas often initiates below the surface and can vary significantly from tube to tube. In addition, extensive corrosion on the metal surface makes the technique more difficult and time-consuming.

In thick-walled pipes, where creep damage initiates at the surface, the limitation is expected to be less a concern as more results of applications allow researchers to relate surface damage to inner-diameter or midwall cracking. Already, surface replication is seen as a valuable screening technique that affords the selectivity and focus required for more-extensive evaluation.

For SH/RH tube sections, where surface replication is not appropriate, EPRI is contemplating a method for predicting remaining life on the basis of steam-side scale thickness and tube wall thickness measurements. The current practice of accelerated high-temperature creep rupture tests does not take into account changes in temperature and stress that occur in SH/RH tubes from fire-side corrosion and steam-side scale buildup. Under a proposed contract, it is anticipated that EPRI will be comparatively evaluating remaining life predictions obtained by the scale method with those of conventional procedures.

Spreading the word

Strong industry interest in EPRI's R&D work on new tools and methods for pressure part life assessment is already apparent. Evidence that the research concerns a generic class of problems common to nearly all fossil fuel power plants may be found in the number of utilities that have approached EPRI about participating in subsequent plant inspections and related projects. Moreover, two industry advisory groups consisting of manufacturers, utilities, and other technical experts have helped to disseminate some of the preliminary results as they have become available. When these ongoing EPRI projects are completed, several methods with various degrees of accuracy for life assessment and various degrees of associated cost of evaluation will be available to utilities, so that each utility can choose its own preferred method, depending on its individual needs and resources. ■

Further reading

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This article was written by Taylor Moore. Technical background information was provided by Ramaswamy Viswanathan, Research and Development, and John Dimmer, Coal Combustion Systems Division.

DOE Progress in Electric Vehicles

Efforts under way at the Department of Energy are bringing electric vehicle commercialization closer to reality.

Searching for alternatives to decrease the use of foreign oil in 1976, Congress enacted the Electric and Hybrid Vehicle Research, Development, and Demonstration Act. This act created an office within the Energy Research and Development Administration (ERDA) to conduct research on improving electric vehicle (EV) performance, to support demonstration programs, and to provide loans to potential manufacturers.

Eight years later, the Office of Vehicle and Engine Research and Development within the Department of Energy (DOE) is now continuing the work started at ERDA. With a FY84 appropriation of $11.7 million, the program focuses R&D on the most promising battery technologies for mid- to late-1980 application: namely the lead-acid and nickel-iron batteries. Other advanced technologies for EV use in the 1990s are also being evaluated, including zinc-bromine, sodium-sulfur, and lithium–metal sulfide batteries and fuel cells. Work is under way to develop ac and dc advanced propulsion systems for integration with experimental EV battery systems in proof-of-concept vehicles. Additionally, fabrication, testing, and evaluation of hybrid vehicles are continuing.

Overcoming Obstacles

Through concerted research efforts, DOE (along with other stakeholders, including utilities and EPRI) has made progress in removing many of the drawbacks that have prevented widespread use of EVs. For instance, DOE has extended both the travel distance and the battery life cycle (the number of times a battery can be discharged and recharged) of EVs.

Paul Brown, director of DOE's Electric and Hybrid Vehicles Division, explains, "At the program's inception, an electric car could only reach a top speed of about 50 miles per hour [80 km/h], and could travel just about 40 miles [64 km] in city driving before it had to be recharged. In addition, the batteries had only a one-year life, or less. Through research in lead-acid batteries, however, prototype electric vehicles can reach speeds in excess of 65 miles per hour [105 km/h], and have a range of 80 miles [129 km] in city traffic. These batteries now have a two-year life."

Through DOE work, the initial cycle life of 100 has been increased to 250 for lead-acid batteries. Brown adds that a nickel-iron battery under testing has exceeded 908 discharge cycles, which is equivalent to more than 60,000 vehicle miles (96,500 km), and is still going strong.

Among the promising near-term battery advancements is one called the Gel Cell, a lead-acid battery using a jellylike electrolyte. Developed by Globe Johnson Controls, Inc., it offers reduced maintenance and hydrogen gas evolution, improved energy efficiency, adequate energy storage capacity, and a competitive first cost, compared with other lead-acid-type batteries. Range, however, remains limited. "Gel Cell batteries for EV application are not yet commercially available," says Brown, "as they are still in the development stage."

Progress is also being made in prototypes for future application. Stresses Brown, "While zinc-bromine batteries have the promise of being low in cost with good maintainability, a great deal more work is needed to develop the battery for EV application. With zinc-chlorine batteries, a 200-mile [322-km] range has been achieved before recharging, but a practical and reliable EV system needs to be developed. As engineering prototypes, these batteries are currently very high in price. Also costly are nickel-zinc batteries, which can achieve long cycle life. Lithium–metal sulfide batteries are being evaluated for possible application but require good insulation, both to retain the power and to protect the occupant in the event of an accident." Brown explains that these problems appear to be solvable, but not in the near term.

Equally as important as DOE's battery research is work under way to improve the EV propulsion system. Evaluations of existing commercially available technology were undertaken, and the development of advanced controllers, motors, transmissions, and propulsion subsystems was escalated. Special emphasis was given to developing lower-cost, higher-performance technologies and higher-efficiency dc and ac EV propulsion subsystems and components. These efforts are resulting in significant weight and volume reductions—on the order of 50% of the power train systems available in 1976.

Development, however, is not limited to electric vehicles. Hybrid vehicles, which allow for either electric or gasoline power, are also being pursued. As with the purely electric vehicle, the hybrid has achieved marked improvement during the past several years. In a recent EPA test, for example, a hybrid comprising ten 12-volt lead-acid batteries and a 4-cylinder engine achieved a city mileage equivalent to 120 miles per gallon (51 km/L) on a dynamometer test. But the practicality of the hybrid, given its complexity and cost, remains in question.

DOE is continuing to sponsor test and evaluation activities whereby electric and hybrid vehicles can be evaluated under actual on-the-road commercial transportation conditions. More than 39 private and public sector operators located throughout the country are participating in these field tests involving some 650 EVs, led by the U.S. Navy with 170 vehicles at 21 naval facilities. The objective of the vehicle fleet testing is to seek solutions to generic problems encountered by vehicle users that are inhibiting the acceptability of EVs for performing normal daily operations. "Through these tests, the operation and maintenance costs of EVs can be compared with those of conventional vehicles in the same fleet. The problem today is that the first cost of an EV is very high since all these vehicles are handmade and no one is mass-producing them," states Brown.

If mass production is required, it would ultimately be up to the large automobile manufacturers to produce an EV with characteristics and costs to make it a market success. With EV life-cycle costs high—because of the short life and high maintenance costs of currently available batteries—and with the current price of gasoline well below $2.00 a gallon (53¢/L), an auto manufacturer will have a hard time finding the incentive to invest in large-scale EV production.

Load-Leveling Success

The utility industry, on the other hand, does have an incentive to foster development of the electric vehicle: it is an excellent load-leveling mechanism if a large fleet of EVs could be recharged at night during off-peak times. Brown explains that fleet operators have significant interest in operation and maintenance costs—or the life-cycle costs—of their vehicles. "Fleet operators are looking for a vehicle that lasts longer than passenger cars and are usually willing to pay more initially. Actually, in tests the EV has demonstrated lower operation and maintenance costs than the equivalent diesel- or gasoline-powered source."

Convinced of the potential appeal and practicality of the EV and realizing that automobile manufacturers have little financial incentive to produce them, the electric utility industry has embarked on a mission for commercialization. Industry proponents of EVs, including Arizona Public Service Co., Consolidated Edison Co. of New York, Detroit Edison Co., Long Island Lighting Co., Southern Company Services, Tennessee Valley Authority, and Wisconsin Electric Power Co., recently joined to create the Electric Vehicle Development Corp.

EVDC will consolidate EV interest nationally and seek to attain quantity production of electric cars and trucks within the 1980s. It will apply research results from DOE and EPRI to help achieve EV commercialization. A broad program in EV battery development and vehicle systems development is under way at EPRI. In addition, EPRI is seeking to ensure that utility needs and capabilities are considered in plans for the development and public use of EVs. The corporation can

Brown

then use the research and test results to determine the best applicable technologies and to spur EV production.

In the meantime, the United States is not the only nation pursuing EVs. Extensive work is under way in Great Britain, Japan, and West Germany. Great Britain employs about 40,000 electric milk trucks, although these are not truly capable of performing as passenger cars during daily operation. Major Japanese firms are collaborating on the development of a cost-efficient electric passenger car. Work is also under way in Belgium, Denmark, France, and Italy. Such widespread international interest in the EV suggests its desirability as an efficient means for reducing the consumption of petroleum and lowering mobile-source air pollution.

In a recent letter to his constituents, Senator James A. McClure, chairman of the Senate Committee on Energy and Natural Resources, endorses the DOE program as an effort to create a viable EV industry in this country. McClure states, "The successful commercialization of electric cars will offer American consumers many advantages over conventional automobiles, including lower operating costs, less chemical and noise pollution, and most important, an alternative to the use of petroleum products in transportation."

McClure goes on to stress that if only 10% of the nation's passenger cars and light trucks are powered electrically, approximately 500,000 barrels of oil per day could be saved by the year 2000. And with full-scale national support, Brown believes that EV commercialization can be achieved within the next 3–5 years for commercial vehicles and 5–10 years for passenger cars. ■

This article was written by Ellie Hollander, Washington Office.

Advanced Battery Tests Under Way at BEST

The first advanced battery system built expressly for utility load leveling is now operating at the Battery Energy Storage Test (BEST) Facility.

A 500-kWh zinc chloride battery system built by Energy Development Associates (EDA), a subsidiary of Gulf+Western Industries, Inc., has become the first advanced battery to be installed at EPRI's BEST Facility in Hillsborough Township, New Jersey. The test program, cofunded by EPRI and DOE, is expected to continue for six to nine months.

To qualify the battery for installation at BEST, EDA tested it at Detroit Edison Co.'s Charlotte substation in downtown Detroit. The battery operated successfully for 11 cycles with energy efficiencies as high as 63%. It is projected to have a long life under a severe daily duty cycle.

Battery energy storage systems can assist electric utilities in load leveling because a utility can store energy in batteries at its substations when demand is low and release this energy during peak demand periods. Most utilities now maintain expensive generating facilities to meet the peak demand periods of their customers. The advanced battery system also has applications for other industries that have widely varying power demands.

The storage system contains 10 series-connected zinc chloride battery modules, each capable of delivering up to 50 kWh (e); power conditioning and control equipment and other auxiliaries complete the system. Because it consists largely of inexpensive and abundant materials—zinc, chlorine, plastics, and graphite—the battery can be produced economically and quickly. Pumps, motors, and various titanium components represent only a small percentage of total materials. Walter Keryluk, manager of EDA's Greensboro, North Carolina, plant, where the cells are produced, notes that "in the past it took two months to build a battery. Now we can put one together in three weeks. If we go into a production operation, we can turn out eight batteries a day."

EDA also has a second-generation, modular Flexpower system design that is being readied for initial production this year. Demonstration sites are being sought for installation of 2-MW to 10-MW prototypes. ■

Canadian Research Now Included in EPD

EPRI's research and development information system—the Electric Power Database (EPD)—was recently expanded to include research projects sponsored by the Canadian Electrical Association and Canadian electric utilities, such as Ontario Hydro, Hydro-Quebec Institute of Research, and British Columbia Hydro. The addition of Canadian research information significantly expands the scope of EPD and should result in increased convenience for users because more worldwide electric utility information is now available from a single source.

EPD currently includes more than 13,000 research records. The projects listed in EPD represent the latest fronts of electric utility industry research and address relevant economic and environmental concerns, as well as new technologies. New projects are added regularly and completed projects are retained for reference. Because projects are added to EPD when contracts are initiated, EPD users are assured of being made aware of research in progress well in advance of any publications documenting results.

The research data from the Canadian Electrical Association will be entered in the same format as other EPD records prepared by EPRI's Technical Information Center staff. Entries include the project title, sponsors, contractors, funding, a project description, keywords, subject classification codes, and publications resulting from the research.

EPD is available for computer-assisted on-line retrieval internationally through Dialog Information Services, Inc., and DOE.

The most recent printed version of the data base, the annual three-volume *Digest of Research in the Electric Utility Industry* (or *Digest-83*), is now available. The latest edition is about 24% larger than the 1982 document and includes records for EPRI research projects as well as utility- and industry-sponsored research.

Volume 1 covers research completed from 1973 through 1980. Volume 2 describes research from 1981 to 1983 and Volume 3 provides subject and corporate indexes to both Volumes 1 and 2. Copies, which may be ordered from the Research Reports Center, are free to EPRI member utilities; the nonmember price is $25 for the three volumes, or $5 for Volume 1 and $20 for Volumes 2 and 3 as a set.

In addition, the most recent edition of *EPRI Research and Development Projects* is also available (TI-3000-SR). This report, arranged by technical division, presents a comprehensive list of EPRI-funded research projects.

More information on EPD, *Digest-83*, and R&D projects is available by contacting the Technical Information Center (415) 855-2411. ■

Mobile Laboratory Gathers Data on Transmission Lines and Birds

Several electric utilities are now using or plan to use an EPRI-developed mobile laboratory to evaluate the environmental effects of transmission lines on birds in flight. Southern California Edison Co. currently has two mobile laboratory units in operation, and expressions of interest have been received from the Air National Guard and from many conservation agencies.

The mobile laboratory was developed in response to concerns about how transmission lines affect flying birds. In recent years, a lack of data and an abundance of speculation on the impact of transmission lines on avian flying behavior have resulted in costly delays, route changes, and refusals of permits for line construction projects. Bird mortalities from collisions have drawn particular attention to existing transmission lines.

First introduced and tested in 1982, the mobile laboratory is equipped with radar and electrooptical devices that allow utilities to gather quantitative information in a standardized manner on the flight behavior of birds in the vicinity of transmission lines and specifically on collision mortality.

The laboratory grew out of a project launched in 1979 by EPRI's Ecological Studies Program to study avian interaction with transmission lines. Initial work consisted of acquiring, calibrating, and testing equipment and methods for studying bird flight around power lines and included such observation techniques as radar, night vision devices, and closed-circuit television.

The first mobile laboratory was designed and developed by Clemson University in South Carolina. Operation and performance of the mobile laboratory were evaluated at four sites: Clemson and Charleston, South Carolina; Beaumont, Texas; and Lake Charles, Louisiana. The Texas and Louisiana sites were chosen because of the frequency and diversity of daytime and nighttime bird movements at these locations. During the evaluation, techniques for making and recording observations of birds flying in the vicinity of transmission lines were developed and assessed.

Although the mobile laboratory was designed to gather data for assessing the impact of transmission lines on local and migratory birds, it can also help researchers assess the impact of other electric utility equipment, such as wind turbines and solar collectors.

More information on the mobile laboratory is available from Project Manager John Huckabee (415) 855-2589. ■

New Members Named to EPRI Board

During the 1984 Annual Meeting of Members in Dallas on April 9, two members were elected to one-year terms and three reelected to four-year terms on the EPRI Board of Directors. All five represent investor-owned utilities.

Theodore J. Carlson, chairman of the board and principal officer at Central Hudson Gas & Electric Corp., and John W. Ellis, president and chief executive officer of Puget Sound Power & Light Co., will serve one-year terms on the Board. They succeed members who have completed four-year terms or who have resigned.

Carlson has served on the board of Central Hudson Gas & Electric since 1968 and was named to his present position in 1975. He lives in Briarcliff Manor, New York.

Ellis has been with Puget Sound Power & Light since 1970, when he was named vice president for utility management and chief operating officer. He is a resident of Bellevue, Washington.

Reelected to four-year terms on the Board were Frank W. Griffith, chairman of the board and president of Iowa Public Service Co.; Don D. Jordan, chairman and chief executive officer of Houston Lighting & Power Co.; and Paul D. Ziemer, president and chief executive officer of Wisconsin Public Service Corp. ■

Board Approves Research Projects

The EPRI Board of Directors approved four new research projects at its recent annual meeting in Dallas: a high-sulfur test center, an AFBC conversion project, an EHV cable laboratory, and a distribution automation project.

The High-Sulfur Test Center will include laboratory, minipilot- and pilot-scale facilities to evaluate and develop improved SO_2 scrubber technology for new and retrofit high-sulfur-coal applications (RP2604). Current and future developments resulting from other research projects will be incorporated into the test center, including scrubber performance enhancements, by-product quality improvements, dewatering methods, spray-dry FGD, and integration of plant water management with scrubber design and operation. The Board authorized funding of $1,200,000 for the center during 1984 and 1985. Additional funding requirements may be sought at a future time.

The Black Dog AFBC conversion project (RP2628) will involve converting an existing 100-MW pulverized-coal boiler operated by Northern States Power Co. to a 125-MW AFBC boiler. This conversion project complements the TVA–Duke Power Co.–State of Kentucky new AFBC boiler demonstration and is one of the original industry proposals offered to EPRI in February 1983. The Board approved funding authority of $9,500,000 over five years.

The EHV Cable Research and Test Laboratory, in Yonkers, New York, will use an existing laboratory for tests on newly developed EHV cable and accessories (RP7899). The project has been funded at $3,300,000.

The objectives of the distribution automation and load control system project are to design and develop a digital automated control system, to integrate the system into the operations of a host utility, and to test and evaluate the system's performance (RP2592). The Board authorized a funding level of $7,187,000.

In addition to these new ventures, five existing research projects received increased funding from the Board: the Transmission Line Mechanical Research Facility, increased by $2,780,000 to a total authorization of $22,280,000 (RP1717); the Integrated Environmental Control Pilot Plant, increased by $2,100,000 to a total authorization of $8,300,000 (RP1646); the Nondestructive Evaluation (NDE) Center, increased by $20,000,000 to a total authorization of $36,169,000 (RP1570); a project on thermal annealing of an embrittled reactor vessel, increased by $300,000 to a total authorization of $5,299,000 (RP1021); and a corrosion fatigue characterization of reactor pressure vessel steels, increased by $1,787,000 to a total authorization of $4,450,000 (RP1325). ■

CALENDAR

For additional information on the EPRI-sponsored/cosponsored meetings listed below, please contact the person indicated.

JULY

19–20
Dechlorination System Design and Operations
Chicago, Illinois
Contact: Winston Chow (415) 855-2868

24–26
Chemical and Physical Test Methods for Flue Gas Desulfurization Systems
Phoenix, Arizona
Contact: Dorothy Stewart (415) 855-2609

AUGUST

13–14
Effect of Voltage Change on Energy Consumption
Dallas–Fort Worth, Texas
Contact: Herbert Songster (415) 855-2281

21–22
Seminar: Generator Modeling
Cincinnati, Ohio
Contact: Dharmendra Sharma
(415) 855-2302

23
Seminar: Torsional Fatigue Crack Growth in Large Turbine Generator Shafts
Cincinnati, Ohio
Contact: Dharmendra Sharma
(415) 855-2302

SEPTEMBER

12–14
Life Assessment and Improvement of Rotors for Fossil Fuel Turbines
Raleigh, North Carolina
Contact: Ramaswamy Viswanathan
(415) 855-2450

20–21
BENCHMARK: A Chronological Generation Simulator
Boston, Massachusetts
Contact: Jerome Delson (415) 855-2619

26–28
Symposium: Demand-Side Management
New Orleans, Louisiana
Contact: Ahmad Faruqui (415) 855-2630

OCTOBER

9–11
Chemical and Physical Test Methods for Flue Gas Desulfurization Systems
Atlanta, Georgia
Contact: Dorothy Stewart (415) 855-2609

R&D Status Report
ADVANCED POWER SYSTEMS DIVISION

Dwain Spencer, Vice President

GAS TURBINE PERFORMANCE EVALUATION

EPRI has funded many combustion turbine projects and has received proposals for a number of others that require the selection of alternative components or operating conditions. The turbine manufacturers present conflicting claims on the benefits and penalties of various systems and their design trade-offs. Therefore, EPRI and its utility members need an accurate computer program to evaluate the performance of proposed combustion turbine systems. Such a computer program would allow EPRI to independently determine performance comparisons and to assess the manufacturers' claims.

To evaluate technology in the framework of a power plant cycle analysis, the gas turbine evaluation (GATE) computer program has been formulated. This program calculates the effects on system performance of such elements as compressor bleed locations for turbine cooling, air extraction, different turbine cooling concepts (convective, film, and transpiration), and a heat recovery steam generator (HRSG) with up to three pressure levels and steam turbine inductions. This allows the calculation of power plant performance without the simplified assumptions typical of such computations, which may lead to incorrect conclusions.

One example is the gas-steam combined cycle. An optimization calculation that uses a simple one-pressure-level HRSG would underestimate the steam system efficiency. The conclusion might be that a higher turbine inlet temperature for improved gas turbine efficiency is needed to meet a required overall heat rate for the system. This ignores the alternative of a multipressure HRSG that would increase the steam system efficiency and place less of a premium on gas turbine efficiency.

Another common problem with typical analyses is the oversimplification (and, often, underestimation) of the cooling requirement for gas turbines. The result is that higher turbine inlet temperatures appear to be very beneficial. If cooling requirements are overestimated, however, increased turbine temperature shows little benefit. Thus the correct calculation of this requirement could have a significant impact. EPRI has been working for several years with gas turbine manufacturers to improve the cooling effectiveness of the next generation of gas turbine engines proposed for utility service. Factoring the results of this technology into the cycle analysis will ensure the cooling requirement is calculated more accurately for comparisons.

GATE program

The GATE computer program is applicable to four basic cycles.

- The simple cycle, where the gas turbine exhaust energy is not recovered
- The combined cycle, which uses the gas turbine exhaust energy to generate steam in an HRSG that in turn generates power in separate steam turbine systems
- The steam-injected cycle, which uses the gas turbine exhaust energy in an HRSG to generate steam for injection back into the gas turbine combustor
- The recuperated cycle, which uses gas turbine exhaust energy to preheat the compressor outlet air before inlet into the gas turbine combustor

The analysis performed by GATE for each of these cycles involves primarily the thermodynamics and gas dynamics of air-vapor-fuel mixtures, with a heavy emphasis on details of the flow.

GATE allows for variations within the four basic cycles. For example, the computer program provides for evaporative cooling of the compressor inlet air and for intercooling in the compressor at one or more arbitrary intermediate pressure ratios. Such intercooling may use a surface-type heat exchanger or evaporative cooling with water. GATE computes turbine performance on a stage-by-stage basis and allows specification of reheat combustion between any two stages in the turbine; a supplementary burner may be specified at the turbine discharge as well. As mentioned above, the program also allows the user to specify one-, two-, or three-pressure-level HRSG systems for the combined cycle.

GATE also has a wide variety of realistic turbine cooling options. Turbine cooling, computed separately for each stage, is by compressor bleed air or steam from the HRSG. The user has the option of specifying any physically feasible location in the compressor from which to bleed the cooling air for each rotating or stationary stage. Each cooling-air flow may be used as is, or it may be further cooled by heat exchange or evaporation. For steam cooling, GATE assumes an HRSG to be part of the system, and a variety of cycle variations with extraction steam turbines are possible. Because the user may specify steam cooling at selective stages in the turbine, the cycle in effect becomes a staged steam injection cycle.

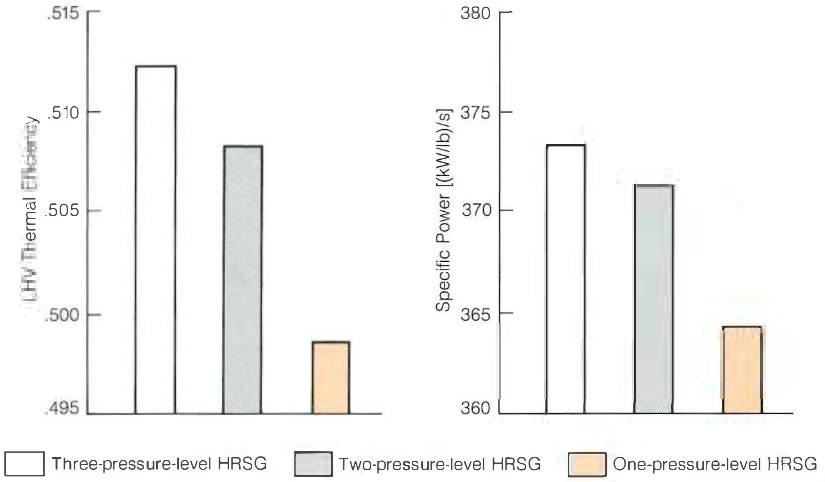
Four cooling techniques are at the user's option for each turbine stage: standard convection cooling (used in current utility turbines), advanced convection cooling (being developed in EPRI's advanced cooling project), film cooling (used in aircraft jet turbines), and transpiration cooling (proposed for future turbines). GATE uses the best available data from EPRI's project on advanced turbine cooling (RP1319), DOE's project on high-temperature turbine technology, and NASA's studies to calculate the cooling flows for each type of cooling technology. The calculation includes end wall and rotor space cooling, as well as cooling for the blades and vanes.

Steam injection into the combustor is a separate engine cycle; however, GATE provides for steam injection in conjunction with the combined cycle as well. The steam injection is in smaller amounts in order to control NO_x emissions in the combustor. A subroutine estimates NO_x levels, using available correlations for standard diffusion combustors, and computes the amount of water or steam injection required to reduce NO_x to a specified level. The overall cycle performance, including the loss of steam turbine power, is calculated self-consistently.

Using GATE

For ease of use, the computer program provides defaults of standard input values for those cycle parameters that the user does not desire to specify. The user can override these inputs with selected values whenever desired. GATE permits calculations for various ambient conditions of temperature and humidity (as well as for inlet evaporative coolers). A typical compressor operating line, built into the computer program, allows for these calculations.

Figure 2 A comparison of the effects of HRSG design on the performance of a reheat intercooled gas turbine–combined-cycle power plant indicates the considerable improvement of two- and three-pressure-level designs over a single-pressure-level unit.



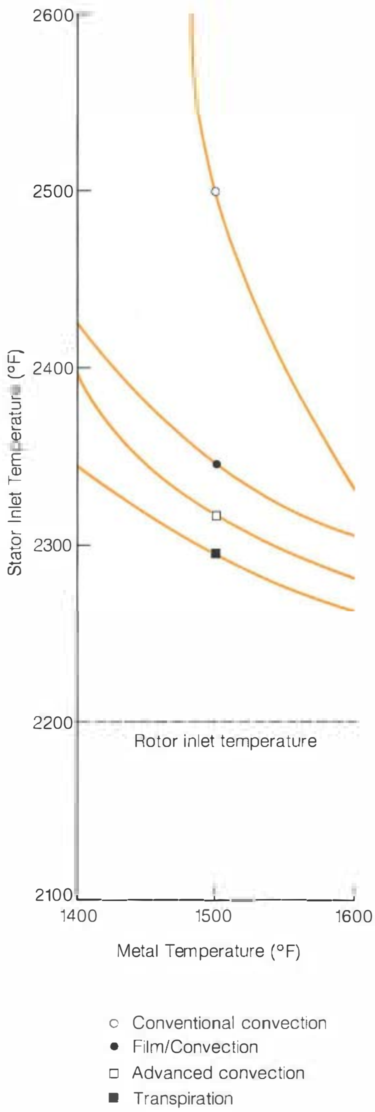


Figure 1 A comparison of the effect of four turbine cooling techniques on the stator inlet temperature for a given rotor inlet temperature of 2200°F (1205°C). For conventional convection cooling there is an especially rapid increase in stator inlet temperature with lower metal temperature because of the major use of cooling air.

The GATE program has been used to calculate the performance of a variety of power plant cycles. Although until now these analyses have had the primary aim of demonstrating the usefulness of the GATE program, some important results have been obtained. The most complete performance analyses have been the calculation of the effects on combined-cycle power and heat rate of various turbine cooling technologies and multipressure HRSG and steam inductions, and the comparison of an intercooled reheat gas turbine with an ordinary nonreheat gas turbine.

Figure 1 presents the results of a comparison of turbine cooling techniques. It shows first-stage stator inlet temperature as a function of metal temperature for various cooling technologies at a first-stage rotor inlet temperature of 2200°F (1205°C). For conventional convection, the stator inlet temperature climbs rapidly with decreasing bulk metal temperature; for the other cooling technologies, the increase is much more moderate. In fact, the 1400°F (760°C) bulk metal temperature, desirable from a durability viewpoint, would be impractical with standard convection as more air would be needed for cooling the stator than would be in the main gas flow.

Figure 2 compares the effects of one-, two-, and three-pressure HRSGs and steam induction on the heat rate and specific power as applied to an intercooled reheat gas turbine combined cycle. Going from the one-pressure to the two-pressure level results in a large improvement. The additional benefit of the three-pressure level is smaller but still may be significant.

Future applications

Further developments of the GATE computer program are in progress, including application to additional cycles (e.g., using exhaust energy recovery to vaporize and dissociate such fuels as methanol prior to injection in the gas turbine combustor). Developments also include making the computer program more user friendly by simplifying inputs and outputs. In addition, GATE will be adapted to various types of computers.

The GATE program will be directed to the calculation of the off-design performance of commercial power plants because of power cutbacks, ambient variations, and turbine and compressor degradations. These types of calculations are of special interest to utility users. *Project Manager: Arthur Cohn*

R&D Status Report
COAL COMBUSTION SYSTEMS DIVISION

Kurt Yeager, Vice President

EVALUATION OF COAL-WATER SLURRIES

Research being conducted in the United States has stimulated interest in the use of coal-water slurry (CWS) as a replacement for fuel oil in utility and industrial boilers. To support the technical growth of this technology, Babcock & Wilcox Co. (B&W) has tested six coal-water fuels supplied by five potential slurry producers (RP1895-3). The objectives of these tests were to investigate the correlation between the chemical and physical properties of the slurries and their handling and combustion characteristics, to establish laboratory procedures for evaluating the quality of CWS, and to develop guideline slurry specifications for application by both producers and users. The results of this work, summarized here, are presented in detail in EPRI CS-3413, Volumes 1 and 2.

Tests and procedures

The B&W test program included laboratory analyses using standard or modified ASTM procedures and newly developed procedures; rheology tests to characterize the flow properties of the CWS fuels; atomization tests, in which each fuel was tested under the same conditions and with the same atomizer; and combustion tests in a 5 million Btu/h furnace, which featured identical firing conditions and the same burner-atomizer combination for all fuels.

The fuels for these tests were produced during 1982. Because slurry producers have modified their preparation processes and quality control procedures since then, the quantitative results summarized here do not necessarily reflect today's state of the art. However, this experimental work should provide a basis for quality control for both slurry vendors and the utilities that will use CWS.

In the course of this project, B&W developed 21 test procedures for characterizing CWS fuels. These represent a first step toward establishing standard CWS test procedures. Tests were developed in five major areas: general properties (e.g., particle size distribution, density, pH), fuel properties (e.g., proximate and ultimate analysis, heating value), rheological properties, stability, and ash deposition.

Significant results

The coal content of the slurries ranged from 70 to 75% (by weight, on the basis of dry coal). Viscosity at room temperature varied from about 500 to 2000 cp (0.5–2.0 Pa·s). At shear rates below 300 s^{-1}, the measured viscosities of the six fuels did not correlate with solids content (Figure 1). This finding suggests that such factors as the coal particle size distribution, the chemical additives used in slurry production, and the characteristics of the parent coal may also be important in determining CWS viscosity. Any given slurry, however, shows decreasing viscosity on dilution (as also illustrated in Figure 1).

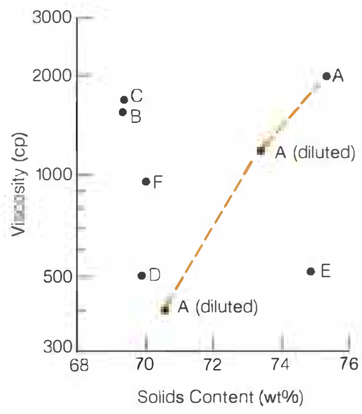


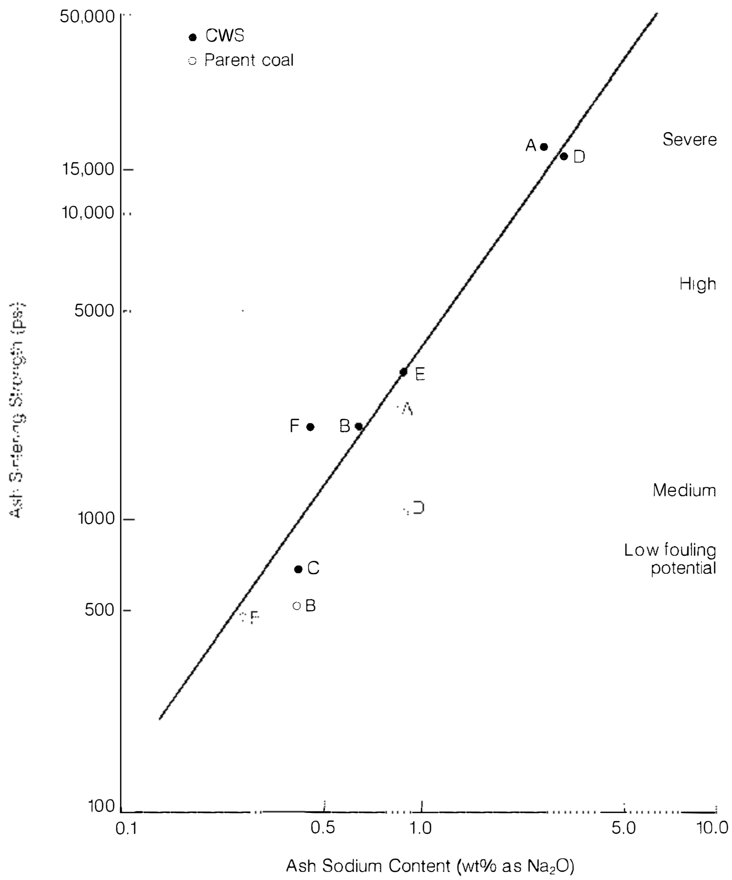
Figure 1 CWS viscosity versus solids content. Tests of six different slurries (*A–F*) at a shear rate of 100 s^{-1} revealed no correlation between solids content and viscosity (as measured by a Haake viscometer). Diluting the slurries did result in a lower viscosity, as shown here for slurry *A*.

Stability and flow properties are a major area of concern to both slurry producers and users. Variables affecting these properties are parent coal surface characteristics, coal particle size distribution, and chemical additives (which are a major proprietary item for slurry producers). Stability tests simulating tank storage and truck, barge, and rail transportation indicated that all of the fuels were relatively stable for up to three weeks; however, it is recommended that transportation, storage, and handling systems incorporate provisions for preventing settling or for reentraining settled material. No differences in settling were noted between tank storage conditions and simulated transportation conditions.

The six CWS fuels exhibited complicated and different rheologies (i.e., flow characteristics), but all were capable of being pumped and fired successfully. CWS viscosity generally depends on shear rate and time at shear. Depending on the chemistry of the additives used, slurries can either thicken (i.e., viscosity increases) or flow more easily (viscosity decreases) as the slurry temperature is raised to about 150°F (66°C). Thus, for some slurries, preheating is precluded as a means of reducing viscosity for atomization. A comparison of pipe flow results with Haake viscometer results indicates that laboratory viscometer measurements can reliably be used to predict the flow behavior of CWS in piping.

The synergistic effects of the parent coal and the additives used in making a slurry determine its basic fuel properties. Because of changes in ash chemical composition re-

Figure 2 Fouling potential of CWS and parent coals versus ash sodium content. The curve presents a standard correlation between ash sintering strength at 1700°F (927°C)—which is used as an index of ash fouling potential—and ash sodium content. (No parent coals were available for slurries *C* and *E*.)



sulting from the additives, the ash deposition characteristics of a slurry can differ from those of the parent coal. Slurries in which a sodium-containing additive was used showed an increased potential for fouling relative to the parent coals. The slurry vendors were notified and have taken steps to eliminate sodium-based chemicals as additives.

In Figure 2 the fouling potential of each parent coal and CWS fuel tested is shown as a function of the sodium content of its ash. The curve represents a standard correlation developed by B&W on the basis of hundreds of coals. It is clear that all the fuels are in substantial agreement with the standard correlation. This provides justification for interpreting the results on CWS fouling potential in terms of the fuels' sodium content.

In atomization tests, slurries with the same viscosity but from different vendors did not produce the same atomization quality under the same operating conditions. No general correlation was found between atomized droplet size and the CWS viscosity as measured in this program. For any one fuel, however, reducing viscosity—through dilution or moderate heating—improved atomization quality (Figure 3).

The six CWS fuels were successfully fired at all the planned test conditions. Stable fuel ignition was achieved without auxiliary fuel with combustion air preheated to 400°F (204°C), a ratio of atomizing air to fuel of between 0.2 and 0.4 (by weight), and no fuel preheat. The properties of the parent coals affected the combustion results in minor and predictable ways; for example, a high volatile-matter content contributes to good ignition stability. However, the overwhelming determinant of combustion performance was atomization quality.

This can be understood in terms of the following proposed mechanism of CWS combustion.

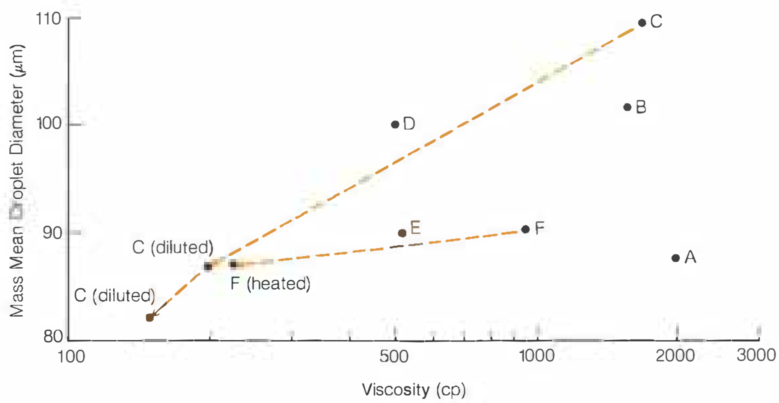
- A single droplet of CWS containing many coal particles is created by the atomizer.
- The droplet begins to dry from the outside, and the coal at the surface may begin to get tacky (especially likely for the high-volatile-matter bituminous coals used in this study).
- Many things can happen at this point, depending on the coal, the furnace environment, and possibly the CWS chemical additive package. For the CWS fuels tested by B&W, the outcome is a single particle of approximately the same size as the original atomized droplet, consisting of all the smaller coal particles "glued" together. It is this agglomerate that must be burned in the combustion process.
- If all the carbon is burned away, the particle becomes friable and a fine fly ash is obtained. At poor carbon conversions, however, the largest fly ash particles tend to be about the same size as the largest atomized droplets.

If this proposed mechanism is correct, then combustion efficiency for CWS firing is strongly dependent on atomization quality—especially on the number of large droplets produced. If a CWS atomizer produces a great number of droplets larger than 300 μm in diameter, combustion efficiency will not be high. This situation is completely analogous to pulverized-coal combustion, in which the number of coal particles larger than 300 μm is carefully limited. Good atomization is also important for stable CWS ignition. Smaller droplets have a higher surface-to-volume ratio, which improves heat and mass transfer rates in the burner ignition zone.

Guideline CWS specifications

The guideline CWS specifications developed by B&W are generic and are not boiler- or site-specific. They call for a stable CWS with the highest solids content compatible with an acceptable viscosity. At a shear rate of 100 s^{-1} and a temperature of 78°F (26°C), a viscosity below 2000 cp (2.0 Pa·s)—as measured by a Haake viscometer—is specified. It is likely that by the time a large-scale utility CWS demonstration is performed, the optimal viscosity for as-fired CWS fuel will be

Figure 3 CWS atomization quality versus viscosity. Although the results for the six slurries showed no general correlation, atomization quality did improve (i.e., mean droplet diameter decreased) when slurry viscosity was decreased by dilution or moderate heating. Atomization was conducted with an atomizing air pressure of 150 psig (1.03 MPa), and viscosity was measured at a shear rate of 100 s^{-1}.



below 500 cp (0.5 Pa·s). Judging from the tests performed, there is no reason to specify a particular rheology (e.g., Newtonian, pseudoplastic, dilatant). Ideally, the viscosity should remain below 2000 cp at all shear rates above about 50 s^{-1}.

For CWS to burn as completely as pulverized coal, at least 70% of the particles in the fuel (on a weight basis) should be less than 74 μm in diameter (i.e., <200 mesh). Tight oil-designed boilers may require finer particles, although such a change in particle size is only useful if the atomizer can perform well enough to take advantage of it. No more than 1% of the particles (by weight) should be greater than 300 μm (>50 mesh).

The specifications recommend that high-volatile bituminous coals (as defined by ASTM) be used in CWS to ensure a safe, stable flame. Also, in line with the results on fouling potential discussed earlier, the specifications recommend against the use of sodium-containing additives in the production of CWS. *Project Engineers: Rolf Manfred and T. Craig Derbidge*

SOLID BY-PRODUCT UTILIZATION

EPRI's subprogram on the management of solid coal combustion by-products covers several areas. It is aimed at developing technology for the selection, operation, and monitoring of disposal sites for ash and flue gas desulfurization sludges; the identification, treatment, and disposal of low-volume wastes; PCB management; and the use of solid by-products. Previous EPRI Journal *status reports (the most recent of which appeared in June 1983, p. 41) have dealt primarily with PCBs and with engineering and economic studies of coal ash and scrubber sludge disposal. This report's focus—by-product utilization—reflects the increased emphasis on this option for solid-waste management by EPRI and the utility industry.*

Under RP2422 EPRI is developing demonstration projects in three areas of by-product utilization: high-volume applications of coal ash, such as in highway construction; medium-volume ash applications, such as in cement and concrete; and high-technology applications, such as alumina recovery. Before implementing these research efforts, EPRI authorized Michael Baker, Jr., Inc., to carry out an exploratory study. The results, published in the *Coal Combustion By-Products Utilization Manual* (CS-3122), include basic information on the economics and technology of by-product utilization, as well as a step-by-step methodology to help a utility decide whether it should consider marketing its coal combustion by-products. This manual is a companion to earlier EPRI manuals on sludge and ash disposal. Together these reports give utilities the information necessary to develop a comprehensive waste management strategy.

High-volume applications

A scoping study was conducted to help define a research program on high-volume coal ash utilization. It concluded that insufficient data are available to predict the suitability of specific ashes and ash-cement mixtures for road base, embankment, and other highway applications. Consequently, some highway and environmental agencies have been reluctant to approve the use of coal ash in such construction. To encourage acceptance of coal ash for routine application, EPRI has designed its research effort to include the following.

- Laboratory testing of a range of ash-cement mixtures (featuring several ash types) to measure properties relevant to road base, embankment, and backfill applications
- Review, evaluation, and documentation of several previous ash utilization projects
- Selection of up to five geographically diverse utilities for demonstration projects to be conducted in cooperation with state departments of transportation, the Federal Highway Administration, contractors' associations, and the National Ash Association
- Development of technical information on each high-volume coal ash used in the demonstrations through construction inspection, physical and chemical testing, and groundwater monitoring (where needed)
- Publication of design and construction manuals and specifications to facilitate greater use of coal ash in highway construction

The University of California at Berkeley has begun laboratory studies to obtain data on the physical and chemical properties of specific fly ashes and to correlate these data with the pozzolanic behavior of the ashes (RP2422-1). A report that evaluates current test methods for determining fly ash performance in cement was published earlier this year (CS-3314).

In January 1984 EPRI selected three sites in Michigan, Georgia, and Colorado for demonstration projects. The Michigan demonstration project, a joint effort of Consumers Power Co. and Detroit Edison Co., involves the design, construction, and monitoring of a half-mile segment of state highway road shoulder made with base material consisting of cement-stabilized fly ash. Completion is planned for 1985. Participating with the utilities are the Michigan Dept. of Transportation, the Michigan Dept. of Natural Resources, and the University of Michigan. In 1984 alone, the Dept. of Transportation expects to complete 141 mi (227 km) of road shoulder work. If fly ash was used, 300,000 yd^3 (229,400 m^3) would be needed.

The Georgia demonstration project, a joint effort of Georgia Power Co. and Southern Company Services, Inc., involves the design, construction, and structural and environmental monitoring of a 1.6-mi (2.6-km) section of two-lane state highway located about 100 mi (160 km) east of Atlanta. The project will incorporate coal ash in the highway in three ways: (1) by using a lime–fly ash mixture to stabilize a subgrade soil layer, with fly ash that has been collected and stored dry; (2) by using cement-treated fly ash in the base course, with fly ash that has been ponded, then excavated and placed in a landfill; and (3) by using cement-treated pond ash (fine and coarse) in the base course. The ash will be placed in three different highway cross sections, each 1000 ft (0.3 km) in length, for comparison with the standard design. The Georgia Department of Transportation will review the highway's design and construction to ensure proper use of the coal ash. Construction is scheduled for early 1985.

A third demonstration project, planned for 1986 construction, involves a 4000-ft (1.2-km) section of state highway in Colorado. Type C (self-hardening) ash will be used to stabilize dune sands for the road subbase. Because Type C western subbituminous coal ash has a fairly high calcium oxide (lime) content, a vigorous cementitious reaction occurs when the ash is combined with water. Its self-hardening characteristics make this ash a good soil-stabilizing agent, although care must be taken in handling so that it does not set before placement.

Such highway applications have the advantage of consuming considerable quantities of ash while imposing only minimal specifications on ash quality. For example, the road base in a two-lane highway could require as much as 30,000 tons of ash per mile. Given the need to replace or upgrade major stretches of U.S. highways, the potential growth in the coal ash market is large.

Medium-volume applications

Last year over three million tons of fly ash went into cement and concrete products. Although only about 25% of fly ash passes the rigid ASTM specifications for use in such products, the potential for growth in this market is also large. These medium-volume, medium-technology applications include the use of coal ash in asphalt, blocks, bricks, and roofing granules, as well as in cement and concrete. The success of such applications depends to a large degree on the ash's chemistry; a fly ash that meets certain quality criteria can add strength to the end product because of its pozzolanic properties.

Despite the potential advantages of using fly ash in cement and concrete, the lack of experience with such a product's properties, handling characteristics, and general behavior as a construction material has hampered wider use. This lack of familiarity, coupled with the variability of fly ash from different kinds of coal burned in different kinds of boilers, can lead to problems unless the material is fully characterized and its effects well understood.

EPRI issued a contract to identify factors important for stimulating fly ash utilization in the cement and concrete industry (RP1850-2). After interviewing many people active in this industry and in the ash utilization area, including representatives of 16 organizations, the contractor concluded that a better correlation between the physicochemical properties of an ash and the properties of the end-use products was of key importance. Thus EPRI is preparing a project to characterize several fly ashes and to correlate their properties with the end-use characteristics of a variety of cement and concrete products prepared by using different proportions of fly ash.

In addition, EPRI is planning two projects to provide better documentation of utility uses of fly ash and to demonstrate the improved pumping and handling properties that result when fly ash is added to concrete. The first project, by making utilities more aware of the potential in-house applications of their own waste material, will help them convince cement and concrete contractors that using fly ash in their mixes will produce an acceptable—indeed, often superior—product. The second project, which will involve both demonstration and documentation, will show that concrete mixes containing fly ash are more easily pumped and handled than mixes without ash.

High-technology applications

The goal of research in this area is to transform a coal combustion by-product, fly ash, into this country's sixth most abundant natural resource by developing a process for economically extracting metals from the ash. Through the recovery of these metals, utilities could not only reduce disposal costs and land requirements but also realize by-product sales revenues.

EPRI began funding research into ash metal extraction at Oak Ridge National Laboratory in 1979. The primary objective at that time was to find a low-cost process for removing the readily extractable metals from fly ash in order to make the remaining material less leachable. A process was discovered that met this objective in the laboratory and, moreover, produced metal oxides of sufficiently high purity to suggest the possibility of commercial sale and profitable operation. This process involves the leaching of fly ash in hydrochloric acid.

During 1982–1983 Kaiser Engineers, Inc., worked with Oak Ridge National Laboratory under EPRI contract to develop a thorough engineering and economic assessment of a commercial-scale plant that would use the direct acid leaching process, in conjunction with separation and purification processes, to remove metal oxides and other salts from fly ash. A conceptual commercial design and cost estimates were developed for the plant, which was assumed to process one million tons of fly ash (on a dry basis) yearly and to be located next to the Tennessee Valley Authority's Kingston coal-fired power plant. Process heat requirements for the recovery plant were to be met by a steam boiler. It was decided to include a cogeneration power plant to meet process electricity needs. The cost estimates developed by the contractor covered capital, operating, and maintenance requirements; revenue projections were based on several selling prices for the principal products. This evaluation is presented in a three-volume final report (CS-3544) published this spring. Among the major findings are the following.

- The capital cost requirements of the recovery plant were estimated at $244 million.
- The plant would annually produce about 150,000 tons of alumina, 102,000 tons of ferric oxide, 46,000 tons of gypsum, 81,000 tons of alkali salts, and 857,000 tons of spent fly ash; in addition, the cogeneration plant would produce 1940 MWh of excess energy.
- The projected rate of return for the optimized base case process for producing alumina and the other by-products listed above is over 25% per year.
- Producing anhydrous aluminum chloride instead of alumina could potentially reduce the plant's capital cost to $208 million and increase the rate of return to nearly 50% per year. The cost of producing aluminum from anhydrous aluminum chloride is 30% lower than the cost of producing it from alumina by traditional methods.

In April 1984 Phase 3 of the ash metal recovery project began. Over the next two years the main thrust of the work will be to obtain additional data to support commercialization, to solicit aluminum and chemical industry support for the major demonstration projects necessary to commercialize the process, and to refine the economic studies. Utilities interested in having their ash resource evaluated are encouraged to contact EPRI. *Subprogram Manager: Dean Golden; Project Manager: Ralph Komai*

R&D Status Report
ELECTRICAL SYSTEMS DIVISION

John J. Dougherty, Vice President

POWER SYSTEM PLANNING AND OPERATIONS

Transfer capability objectives

Power interchanges between utility companies are occurring at an unprecedented volume. In 1981 Canada-to-U.S. sales alone were 34,000 GWh—equivalent to the total 1981 energy sales to customers of Consolidated Edison Co. of New York. The ability to transmit power between utility operating areas is called transfer capability, and an appropriate level of this ability is called a utility's transfer capability objective. The need to reduce capital spending and the savings possible from exploiting production cost differences in different U.S. regions increase the importance of determining transfer capability objectives. Once determined, objectives can be compared with transfer limits to decide whether capital expenditures to increase transfer capability are necessary or justifiable.

Although transfer capability objectives are chosen to achieve one or more purposes (such as sharing excess reserve capacity, obtaining lower-cost energy, or reducing dependence on a single fuel type), many other factors must also be considered. Combining all factors to make a decision requires extensive analysis and judgment. The need to consider more than two utility operation areas complicates the problem manyfold.

Responding to those analysis needs, Power Technologies, Inc., has developed and tested a procedure and appropriate computer programs by which a utility can compare the costs and benefits of interconnection, thereby choosing the appropriate level of transfer capability (RP1960). The engineer begins by using traditional analysis methods to identify the transfer capability, cost, and attributes (such as reliability and production cost) of a variety of planning options. The tools of this project are then brought into play to mathematically expand the data available and to perform a trade-off analysis of interconnection and other strategies. The most desirable combination of plans is sorted out and the engineer then chooses the best-balanced one, which has a specific transfer capability associated with it.

This project has produced a new, useful, well-documented approach, which was tested on a realistic utility problem. One advantage of this approach is that the judgment of the planner is assisted by organizing and extending the planning techniques now used. Potential users should understand, however, that the initial effort to use these results may be large, depending on present planning practices, and that the results presume the existence of a statistical analysis package and an elementary knowledge of its use. The procedure is documented in a two-volume report (EL-3425); the package of computer programs, called TRADE, is available from EPRI. *Project Manager: James V. Mitsche*

Fast stability analysis

For over 35 years researchers have sought a method for calculating the stability of a power system without using today's expensive, time-consuming, step-by-step simulation—that is, a way to calculate stability directly. Methods that were successful in small system simulations failed when larger, more realistic problems were posed.

In an earlier project a direct stability method was developed that successfully analyzed medium-size systems (RP1355-3). Now Ontario Hydro has expanded these computer programs to accommodate 1500-bus systems (RP2206). Full-scale testing is under way to demonstrate applications and shortcomings, if any, of this technique.

Results thus far show that the technique is providing correct answers, but one part of the method becomes exceedingly slow as larger systems are studied. Various techniques derived from the mathematics and the physics of the problem are being incorporated to speed up the calculations and make the method less sensitive to system size. In principle, this stability calculation should take no longer than a load flow; it is currently much slower than that.

Barring unforeseen difficulties, a practical direct stability analysis program will be available for utility acceptance testing in 1984. This will be a significant step forward, even though the method will require further development over many years to remove inherent modeling limitations. We envision that direct stability methods will not replace traditional methods in the foreseeable future. Rather, they are seen as a powerful complement to these methods, serving as a screening tool to improve the quality of engineering studies and productivity. Direct stability analysis may also enable one to address many applications in dynamic system reliability and security analysis that are not now amenable to computer analysis. *Project Manager: James V. Mitsche*

TRANSMISSION SUBSTATIONS

Light-triggered thyristors

Light-fired thyristors were successfully demonstrated in one phase of a Westinghouse Electric Corp. static VAR generator at Minnesota Power & Light Co. (RP567, RP750; *EPRI Journal,* October 1981). After more than a year of operation, the light-fired thyristor phase was removed in October 1981 and operation resumed with the original electrically fired thyristors. All light-fired thyristors were found to be in good operating condition. Meanwhile, Westinghouse was developing improved, second-generation thyristors, which provided internal self-protection that automatically switched on in case of overvoltage or failure of the light signal. This safety feature permits fewer thyristors in a 15-kV stack, thus reducing both equipment cost and power losses. Westinghouse has now manufactured, packaged, and tested a sufficient number of second-generation light-triggered thyristors for the planned field trial.

However, what is believed to be a partial failure of the cooling system of the original VAR generator, which failed to trip the protective relays, caused severe overheating and damage to the entire unit. Representative samples of the electrically triggered thyristors have been sent back to Westinghouse to determine which, if any, have survived and to find if a failure pattern can be established. A decision on continuing the original plan to test the new light-fired thyristor phase awaits evaluation of the overall damage.

The ultimate aim of a related project with General Electric Co. was to develop a light-triggered thyristor (LTT) capable of one-for-one replacement of electrically triggered thyristors; these are most needed in the demanding HVDC application where hundreds of thyristors are connected in series and must be turned on and commutated off simultaneously (RP669-2). This goal was first accomplished with a 2.6 kV, 1000-A LLT.

However, as higher-voltage thyristors were developed, the 2.6-kV LTT became obsolete, and the new goal was set at 5 kV. Actually, a part of the earlier program was to investigate a means to scale up the voltage to 5 kV and to eliminate protective circuitry, where possible, by incorporating protective functions into the thyristor, particularly voltage break-over (VBO) protection. Because both 5-kV turn-on and VBO protection involved safe turn-on at high voltage, these two problems were qualitatively similar.

During the development of the early LTT, for example, it was found that the thyristors could survive high-voltage turn-on if at least one amplifying stage was used and if current in that stage could be controlled with a resistor during turn-on. In the experiment the amplifying stage and resistor were separate, discrete components. In this project both are successfully incorporated into a 5-kV LTT, which was the prime goal. The basic problem is the high turn-on energy, the product of a large turn-on voltage and a fast rising, or high di/dt, device current. In normal HVDC operation the turn-on voltage would rarely exceed 3200 V. In a VBO turn-on the situation is similar qualitatively but much worse quantitatively because the turn-on voltage is now at the device avalanche breakdown voltage, perhaps 5–6 kV, and the area that avalanches may only be several mils in diameter.

To make a successful 5-kV device, controlled turn-on was developed during the later phase. This allows even a weakly gated LTT to surpass its electrically gated counterpart in di/dt capability by a wide margin. In doing so we also made, with its 1-mA gate sensitivity, the most sensitive high-voltage LTT and, at 5 kV/μs, the highest dv/dt thyristor yet reported. In addition, the device seems to have a measure of built-in dv/dt and transient VBO protection through its controlled turn-on action.

During the current project the foundation was also laid for ion implant processing, and work began on a more effective edge termination. These techniques, if combined, could lead to higher current and voltage ratings from the same starting wafer.

All phases of this program were greatly assisted by a substantial General Electric computer modeling commitment. Follow-up work in the realm of higher-voltage LTTs will continue under RP2443-1. *Project Manager: Gilbert Addis*

UNDERGROUND TRANSMISSION

PPP laminate for low-loss, 138–550-kV pipe-type cable

The most attractive insulation material under development for 138–550 kV underground transmission is a three-part laminate of cellulose paper–polypropylene-film–cellulose paper (PPP). When combined with a compatible dielectric fluid, this new low-loss insulation system maintains the best properties of the synthetic film and the fibrous cellulose and is expected to offer many advantages to utilities. (PPP-insulated cables were discussed in the *EPRI Journal* issues of June 1983 and December 1982.)

These developments can account for appreciable savings for new low-loss underground transmission requirements or for replacements and upgrading (to two voltage levels) where existing circuits are no longer adequate for present or future system conditions. A third advantage is that existing manufacturing, installation equipment, and methods are applicable to PPP insulation, and no major capital investments by traditional suppliers will be required.

In the United States the requirements for increased underground transmission have been met, for the most part, by the continuous developments and improvements in taped-paper, oil-impregnated, high-pressure, oil-filled (HPOF) pipe-type cable systems. However, with paper insulation, the dielectric losses above 500 kV are prohibitive, as these losses increase with the square of the operating voltage, and the inherent limitations of paper become predominant.

Under a previous EPRI–DOE project, cost-shared by the contractor Phelps Dodge Cable & Wire Co., a 765-kV PPP-insulated pipe-type cable was developed in which the dielectric losses and power factor were less than one-third those for paper (RP7812). The increased dielectric strength permitted a large reduction in insulation thickness corresponding to an increase in electric stress to 23.7 kV/mm (603 V/mil), compared with paper at 15 kV/mm (380 V/mil). A prototype sample is under continuous test for the second year of life-testing at Waltz Mill Underground Cable Test Facility, with test results demonstrating excellent stability at temperatures up to 105°C and applied voltages to 125% of rated.

Economic studies under RP7880 indicate that because of the higher dielectric strength with PPP (25–30% higher than for paper), reduced insulation and reduced dielectric losses are cost-effective at commercial voltage ratings, including 138, 230, and 345 kV.

The study indicated that smaller cables, longer lengths, reduced pipe sizes and oil requirements, and reduced dielectric losses over a 40-yr operating life showed savings in total annualized costs of $111,000 per circuit mile for the 431 circuit miles of 138–345-kV cables in the survey.

In another study involving 259 conductor miles of 500-kV cables, with PPP insulation replacing paper a 25% increase in electric design stress permitted a cable diameter reduction of 11%. As a consequence, shipping lengths could be increased from 240 m (787 ft) to 530 m (1739 ft). This advantage made possible a reduction in manholes (from 575 to 260) and in number of splices (from 1725 to 780). The estimated savings in reduced manholes and splices exceeded $50 million, and the installation schedule could be shortened by seven years.

The higher dielectric strength of PPP insulation can be used to substantially reduce the insulation thickness, compared with that of existing paper-insulated pipe-type cables. It appears technically and economically feasible to upgrade existing underground transmission by two voltage levels by replacing paper cables with reduced-wall PPP cables, using the existing pipes and manholes. The estimated savings are some 40% of the cost of a new installation and achieve an increase in MVA capacity of three to four times. Assuming, for example, the replacement of 12% of the existing 3000 circuit miles of underground transmission in the United States, the estimated savings would be more than $150 million.

Cable model tests and results on 230-kV and 345-kV prototype cables confirmed the high dielectric strength and low dielectric losses of PPP insulation (RP7880). For evaluation purposes, the 230-kV and 345-kV prototype samples were manufactured with 0.335- and 0.535-in PPP wall thicknesses, respectively, approximately half that of conventional paper cables. More-conservative designs may be recommended for commercial cables on the basis of a parametric and economic analysis to be prepared for a user's design guide before the completion of the project.

Additional 345-kV prototype cables will be tested with new joint and termination designs, and a 345-kV sample will be delivered to Waltz Mill for extended life-testing. Demonstration projects for commercial installations with participating utilities are planned as part of the technology transfer, to demonstrate the benefits of this new low-loss PPP insulation for 138–550-kV pipe-type cable systems. *Project Manager: Stephen Kozak*

DISTRIBUTION

Effect of operating voltage change on energy consumption

In 1981 we published EL-2036, the report on Phase 1 of RP1419. In that report, we stated that there appeared to be a sufficiently positive correlation between voltage and energy to warrant continuation of the project through the planned second phase.

Since then we have been fulfilling the objectives of Phase 2.

- To determine by test on sample operating feeders the relationship between energy consumption and operating voltage level
- To develop a computer program that can be used by utilities to predict the relationship for any feeder

Time-clock-controlled voltage regulators and data recorders were used on portions of the distribution systems of Texas Electric Service Co. (Tesco) and Detroit Edison Co. (Deco) so that energy consumption and voltage could be continuously recorded as the voltage was raised and lowered on alternate days. This procedure continued for one year. Statistical methods determined the energy dependence on the voltage level.

Concurrently with the data gathering and analysis, a distribution feeder simulation computer program was being developed. This program is based on a three-phase load flow analysis that permits the power flow during appropriate time intervals to be aggregated to provide energy consumption. By inputting appropriate feeder and load characteristics, the energy (both load and system losses) at any bus voltage level can be computed. Needless to say, this simulation program can be used to study other conditions related to feeder operation, but only the energy function was developed in this project.

The comparison between the field test data and the results of the computer simulation of the Tesco field test feeders showed reasonable correlation between the two. At the time of this writing, a final report on Phase 2 is in preparation, which will include a description of the program and the analysis of the Tesco tests. The Deco tests are still in progress and will be described in a separate supplementary report.

The final report is expected to be available early this summer, and on August 14 and 15 a seminar to discuss the project work and the simulation program will be held at the Dallas–Fort Worth Airport. *Project Manager: Herbert Songster*

Lightning flash density

In the January/February 1984 *Journal* we reported that a project was under way to map the frequency of cloud-to-ground lightning flashes in the northeast region of the United States (RP2431). The area under the surveillance of the East Coast lightning locator network in 1983 was about 1 million km² (386,000 mi²), and over 700,000 ground flashes were recorded that year.

Because the geographic locations of the ground flashes are automatically logged by latitude and longitude, the first ground flash density maps were based on flashes per degree-window (the area enclosed by a degree of latitude and longitude) in order to develop techniques for handling these very large amounts of data.

Figure 1 shows the ground flash density isograph for June, July, and August of 1983. During this period 580,000 flashes were located, establishing a density per degree-window, and plotted on a map as density isograms. The density per degree-window is too coarse to be of practical value, because a degree-window on this map varies from 8000 to 10,000 km² (3000 to 4000 mi²). Consequently, work is under way to plot the isolines in flashes per square kilometer, which is the format used in other parts of the world where flash counting has been in progress for some years.

This work was temporarily interrupted during the winter months to attend to more important matters—namely, the expansion of the network. The network that existed in 1983 consisted of 8 locators that were owned by several different organizations and operated by the State University of New York at Albany. EPRI's involvement includes the expansion of the network to cover the entire north-south segment of the East Coast. Consequently, 10 new EPRI locators were installed and in service before the onset of the 1984 lightning season. The addition of several locators acquired from other sources also helped to extend the coverage of the network (Figure 2).

Currently, 21 locators are in operation, each sending electromagnetic and electrostatic information about lightning strokes

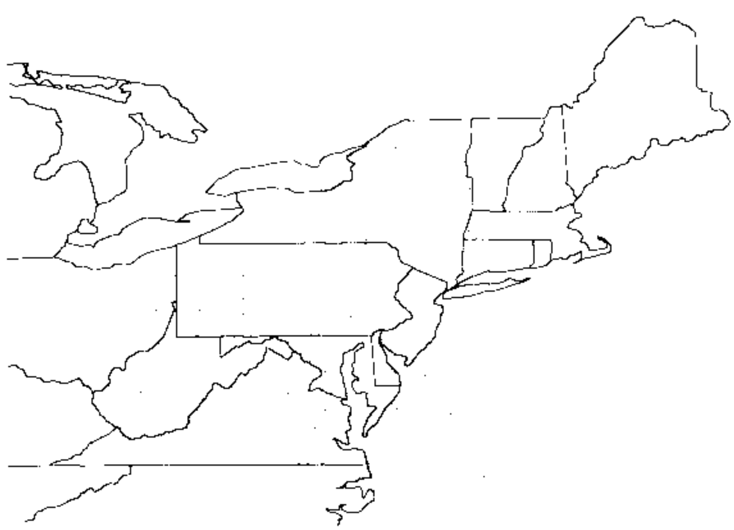
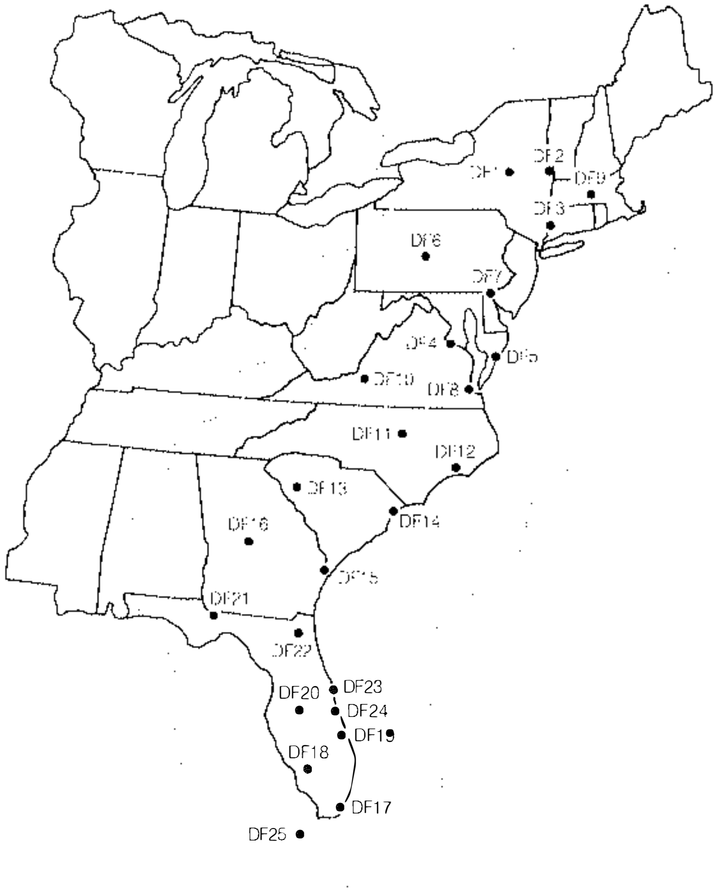


Figure 1 The distribution of 580,000 lightning ground flashes for June, July, and August 1983. The greatest density is 20,000 flashes per degree-window (of latitude and longitude), illustrated by the closed contour around the Chesapeake Bay area. The contour interval is 2000 flashes.

Figure 2 The irregular line enclosing the East Coast region of the United States defines the area under surveillance of the lightning locator network. Twenty-one of the locators (DF1, DF2 . . .) are in operation and negotiations to integrate the remaining 4 locators are in progress. EPRI owns 10 of those between North Carolina and Florida.



within its range to the position analyzer located in Albany, New York. This information includes the direction of the stroke from the locator and the position analyzer; triangulating directions received from two or more locators determines the location of the stroke. By counting closely time-spaced strokes to the same location, the number of strokes per flash is determined. The polarity and peak field strength of the first stroke are also recorded. We are now planning expansion of the network farther west. The extent of the expansion will be determined by budgetary constraints, but we hope the Mississippi River will be the new frontier. *Project Manager: Herbert Songster*

R&D Status Report
ENERGY ANALYSIS AND ENVIRONMENT DIVISION

René Malès, Vice President

UTILITY FUEL PLANNING METHODS

The largest single expense incurred by electric utilities is the cost of fuel. From 1970 to the present, fuel costs have escalated from around 15% of a utility's total costs to over 40%—even over 50% for some systems. Further, fuel prices have not risen steadily but have fluctuated, decreasing as well as increasing. This instability has made planning even more difficult for utilities, who must try both to minimize the cost of fuel (and thereby reduce electricity prices for consumers) and to minimize the risks of reduced earnings to stockholders or owners. In response, utility planners have been developing new analytic tools to support more flexible fuel procurement and management strategies that will increase the utilities' ability to control costs and manage risks. As part of this effort, EPRI's Energy Resources Program is working on a package of tools for analyzing fuel planning alternatives. These tools will enable utilities to select flexible, robust fuel strategies and, in particular, to more effectively incorporate uncertainty into fuel-related decisions.

The objective of the utility fuel planner is to develop fuel procurement and management policies that minimize the busbar cost of generation to customers at an acceptable level of risk to utility stockholders or owners. Until recently that responsibility could be met by negotiating fuel contracts that minimized fuel cost per ton or per barrel as delivered at the plant gate. But the changing fuel markets and fuel requirements of recent years have motivated the industry to develop methods for building more flexibility into fuel planning, to evaluate its fuel costs at the busbar, and to focus new attention on the risks associated with fuel decisions.

Achieving these objectives has been difficult. Uncertainties about electricity demand, fuel prices, and fuel availability make utility fuel planning, procurement, and management decisions complex. In the short term, for example, uncertain fuel burn requirements and uncertain fuel deliveries, together with the industry's need to conserve expensive working capital, make it difficult to select fuel inventory policies. In the longer run, fuel procurement strategy decisions require that the utility make trade-offs between long-term contracts, which offer greater control over fuel price and quality but have limited flexibility, and short-term contracts and spot purchases, which are more flexible but entail greater uncertainty regarding price and quality. Long-term procurement strategies are risky because of such uncertain factors as electricity demand, availability of alternative generation, fuel market conditions, and prices.

A single analytic tool that integrates all procurement and management decisions goes beyond the state of the art in model development. EPRI's research program is divided into projects that examine the individual decisions and choices making up the utility fuel planning process. The projects are designed to develop methodologies that can serve as models of those individual choices and that can be used together to provide an integrated framework for fuel planning decisions.

In the early stages of EPRI fuel research, whenever possible, existing computer models and analytic methods were used or enhanced, particularly models available in the utility industry. As this work has progressed and experience with utility fuel planning problems has grown, researchers have turned to the development of new methodologies and more advanced planning methods. The objective is to construct and demonstrate generic planning tools and to transfer them to individual utilities for their own analyses.

Current EPRI fuel planning research focuses on developing methods and information in these areas: short-term fuel inventory planning; contract mix and trade-offs between fuel procurement options of various lengths and terms; flexible long-term fuel procurement strategies; and the integration of coal quality and plant performance relationships into fuel procurement decisions. An additional research effort is examining how computer models and analytic tools already in use in the industry or under development at EPRI can be applied to improve the integration of utility fuel planning and investment planning.

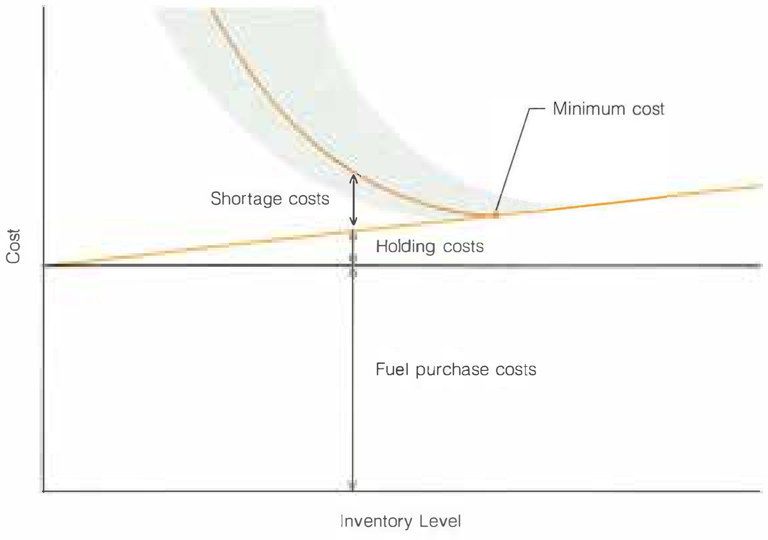
Fuel inventory planning

The goal of this research is to develop analytic tools and guidelines to help utilities set fuel inventories at a level that matches fuel availability to needs while minimizing working capital requirements at an acceptable level of risk. In a joint project by the Energy Resources Program and the Decision Methods and Analysis Program (RP2314; Stephen Chapel and Hung-Po Chao, project managers), a computer model is being developed for utility use in evaluating inventory policies for coal and oil. This project, initiated in June 1983 with Decision Focus, Inc., and Applied Decision Analysis, Inc., is based on earlier EPRI work to document an inventory and spot market purchasing model developed by Carolina Power & Light Co. (RP1947-2).

Fuel inventories enable utilities to conduct power generation operations with relative independence from daily fuel supply fluctuations and problems. Inventories also allow utilities to smooth out fuel supply variations associated with seasonal demand changes and irregular delivery schedules. At the same time, there is a carrying cost associated with holding fuel inventories. Utilities have to trade off these costs against the benefits of holding inventories and the costs that would result from a fuel supply shortage. Quantifying those trade-offs is difficult because of uncertainties about fuel burn requirements, fuel deliveries, market conditions and prices, and the costs of fuel shortages.

Figure 1 illustrates how the model being developed in RP2314 traces the two types of costs involved in the inventory decision—the cost of carrying the inventory (holding cost) and the expected shortage cost associated with reducing burn at a plant because of insufficient fuel. As fuel stocks grow, holding costs rise slowly and are proportional to inventory size. As inventories are reduced,

Figure 1 In fuel inventory planning, utilities must weigh inventory holding costs against fuel shortage costs (which are characterized by a great deal of uncertainty). This graph shows how these costs relate to inventory levels, according to a methodology being developed for use in evaluating inventory policies. The total cost is minimized at the point where the shortage and holding cost curves meet.



fuel shortages become more likely; the utility responds by taking actions that depart from its normal operating procedures, and the expected shortage costs begin to rise rapidly. Because the options available for dealing with inventory shortages (e.g., changing the dispatch order, buying power from another utility, or increasing spot market purchases) have a high cost variability, there is a wide range of uncertainty around the shortage cost curve. In contrast, because holding costs are largely determined by the utility's cost of capital, there is much less uncertainty associated with the holding cost curve.

Adding costs from the two curves together produces a U-shaped curve that describes the utility's expected costs at each target inventory level. (Some readers may note the similarity of this curve to that developed in EPRI's over/under capacity analysis [EA-927, EA-3149-CCM] to describe the cost to consumers of providing adequate generating capacity.) Given the limited information available, defining the shortage and holding cost curves is a key problem for many utilities. Most have had little experience with the inventory shortage region of the curves, and there have been few attempts to build models that help quantify the costs and uncertainties associated with fuel inventory operations, particularly in the critical region where the two cost curves intersect.

The objective of EPRI's inventory research is to develop tools that utilities can use to gain a more quantitative understanding of the costs and risks associated with various inventory planning options. Because both utility management and regulatory agencies are placing a greater emphasis on reducing inventory levels to conserve capital and reduce costs, utility fuel managers need better quantitative information about their inventory costs and risks.

Fuel procurement planning: contract mix

The objective of this research is to develop and demonstrate analytic methods and computer models that can help utilities formulate, evaluate, and explain their fuel procurement strategies.

For baseload and swing fuels, utilities traditionally select a portfolio that includes spot purchases and contracts of various terms. In making procurement decisions, fuel managers must choose from a potentially large range of options. The spot market provides the most flexibility in terms of fuel quantity but reduces utility control over fuel quality and especially costs. Long-term contracts provide increased control over price and fuel quality but are relatively inflexible in terms of quantity, frequently entailing significant take-or-pay charges. Utility fuel managers have the challenge of selecting a procurement mix that minimizes long-run costs and, at the same time, provides enough flexibility to reduce risks to an acceptable level.

The procurement mix problem is difficult because of the uncertainties associated with the fuel decision—uncertainties regarding near- and long-term fuel requirements, unit availability, fuel availability, fuel prices, and fuel quality. For example, a unit's fuel burn requirements are affected by the demand for electricity, the availability of that unit and other units, and the utility's construction and licensing schedule for new units, all of which involve uncertainty. The capacity factor and fuel requirements for a baseload coal unit may be reduced if a planned nuclear unit comes on-line as scheduled and demand grows more slowly than forecast. Similarly, the fuel requirements for an oil-fired swing unit may decrease if lower-priced gas is available or if generation from other options (e.g., hydro, cogeneration, or lower-cost purchased power) is increased. Under such circumstances a utility with a high proportion of long-term contracts could risk take-or-pay penalties or high inventory costs.

From a decision-making perspective, the high cost of fuel has made it increasingly important for utility planners to have tools that help them quantify the costs and risks associated with alternative procurement strategies and that allow them to analyze how alternative strategies perform in different future scenarios. Many planners, believing that no single set of options is optimal, consider it important to develop flexible strategies to provide a hedge against risks. Logically consistent methods are needed for analyzing the value of these strategies.

An initial project with Decision Focus provided a framework for evaluating fuel price and availability while taking into account uncertainties in fuel burn requirements and fuel market conditions (RP1921). Applying that framework to a baseload coal procurement case study, the project developed a methodology for combining those uncertainties to evaluate alternative mixes of contract and spot coal purchases.

On the basis of the insights developed in that project, a second project was initiated with Decision Focus to develop an analytic model and software for use in evaluating contract mixes (RP2359-20). This model permits a utility to consider uncertainties in fuel burn, load growth, fuel availability, and fuel price and to analyze a wide range of alternative mixes. It is currently being demonstrated in the area of oil and gas swing fuel procurement. A subsequent application to baseload and swing coal procurement is planned.

Survey of planning methods

The goal of a project with Arthur Andersen, Inc., is to assess utility fuel procurement issues and options from a business perspective by using insights gained both from recent utility experience and from outside the industry (RP2359-22).

Businesses outside the utility industry have developed many planning methods and analytic tools to support management decision making in the kind of uncertain environment that characterizes fuel planning. Some of these methods may be capable of making a substantial contribution to the fuel planning process. There is a considerable amount of information available about these methods and their application to real-world problems. The principal objective of this research is to study the methods to determine which, if any, show promise for meeting the information needs of utility fuel planners. Follow-on work will adapt and apply these methods to specific utility fuel planning problems.

In addition to planning methods, utilities and other businesses have developed a number of procurement options and strategies designed to increase flexibility. A second project objective is to gather information on the range of strategies available, examine the options that may be applicable to specific utility procurement needs, and provide utility fuel planners with better documentation of these strategies.

Coal quality and plant performance

Differences in, and uncertainties about, coal quality make it difficult to evaluate procurement options. Variations in coal quality affect unit performance, unit availability, and operation and maintenance requirements. Rather than evaluating coal procurement options on a delivered-Btu basis alone, utilities would like to be able to consider these effects and their impact on busbar costs. In a project conducted by the Coal Combustion Systems Division (RP2256), EPRI is evaluating models of the engineering relationships between coal quality parameters and plant performance measures and is developing better data about these relationships.

The objective of a project soon to be initiated by the Energy Resources Program is to integrate the results of EPRI's engineering research into fuel procurement planning analysis (RP2359-30). The availability of better engineering models and data on coal quality–plant performance relationships will enable the development of models for evaluating coal procurement options in terms of the impact of fuel quality on busbar costs. In addition to being applicable to routine coal procurement decisions, the models to be developed in this research will permit utilities to incorporate fuel quality information into major strategic decisions—for example, fuel choice in response to changing emissions control regulations.

Integrating fuel and investment planning

Decisions about new plants or the modification and retrofitting of existing plants are difficult to analyze because of the complex interactions between fuel expenses and capital investments, and the analysis becomes more difficult as more options are considered. Such decisions usually require the integration of information from diverse functional areas of the utility, including planning, operations, engineering, finance, and fuels. For example, utility coal plant investment decisions can entail choices at every point in the fossil fuel cycle—that is, choices on coal type, coal procurement, coal processing, coal transportation, generation technology, and flue gas desulfurization systems. Rarely are all options in all parts of the cycle available to the utility. However, the options that are available are often interconnected: the choice of a specific coal type needed to meet a specific boiler requirement may constrain transportation choices or dictate coal processing requirements or emissions control system design. The complex analysis required for such decisions usually entails extensive communication within the utility.

Integrated analysis is difficult enough when deterministic evaluations are made. When important fuel choices and fuel planning issues are involved, it is far more complex because of the need to explicitly incorporate into the decision-making process the uncertainties that characterize the fuel environment. There are relatively few examples of the vigorous integration of fuel planning and investment planning in complex utility decisions, and even fewer examples that explicitly incorporate uncertainty. However, examples of such approaches do exist outside of the utility industry.

The objective of a project with Dames & Moore and Putnam, Hayes & Bartlett, Inc., is to demonstrate the application of a process for integrating fuel and investment planning in a way that incorporates uncertainty while bringing together several different streams of corporate information (RP2372; Jeremy Platt, project manager). The work is designed to demonstrate the process in the context of utility fuel and investment decision making in response to a change in coal-fired emissions control requirements. Such decisions frequently require the evaluation of options that include both fuel planning choices (regarding coal type, procurement, processing, and transportation) and investment choices (regarding unit fuel design requirements, operating performance, emissions control retrofit options, and investment and financial considerations).

A key aim of the research is to develop an approach that permits the streamlining of the analysis required for such decisions. This streamlining will assist utility planners in integrating and communicating the complex set of information required by utility managers in support of the decision-making process. *Project Manager: Howard Mueller*

VISIBILITY RESEARCH

The relationship between air pollution and visual perception of scenic areas has become an important research topic because of claims that hazes transported from urban areas or emissions from industrial facilities and coal-burning power plants have degraded the air in wilderness areas and national parks. These claims have prompted Congress to require federal regulatory activities "to protect and restore visibility" in such areas. Studies to date have led to an understanding of the nature of the problem, which in turn has stimulated new research approaches. We now know that many factors besides air pollution influence visibility, but systematically planned research is still needed to pin down how various atmospheric emissions and processes influence the appearance of layered and regional hazes. This report summarizes EPRI's efforts in visibility research.

What is visibility?

Most simply, visibility has been defined as the greatest distance at which an observer can just see an object (target) against the horizon sky. This distance, also called visual range, is influenced by a complex set of interrelated factors that control how light from a target is transferred through the atmosphere (radiative transfer) and is perceived by the eye-brain optical system of an observer. Among the factors influencing visibility are the gases and particles present in the atmosphere, as well as the characteristics of the target and the angle between it and the observer. Although a great deal is known about radiative transfer, one of the questions remaining to be answered quantitatively concerns the relative importance of gases and particles in influencing the amount of radiation and the colors reaching the observer.

The atmospheric materials that most influence radiative transfer in the visible range are water droplets (e.g., fog), particles, and nitrogen dioxide (NO_2). The influence of NO_2 is directly proportional to its concentration. Particles alter radiation as a function of not only their concentration but also their size and shape distribution and their chemical composition. They obscure targets because they scatter radiation in all directions. Particles in the diameter range of 0.1–1 μm scatter light more efficiently than smaller or larger particles, and irregularly shaped particles scatter light more efficiently than spheres. Particles that absorb water scatter light even more efficiently. When particles contain soot (black carbon), they not only scatter but also absorb light; this further blocks the radiation from the target to the observer and alters its perceived color.

The blocking and alteration of radiation from targets is called light extinction. Theoretically, one could attribute part of the total extinction to each type of material suspended in the atmosphere—thereby establishing an extinction budget. This budget could then be used to calculate how much various materials influence visibility. If it is possible to identify the emission sources of the materials, these could also be related to the extinction budget.

The current understanding of visibility has enabled researchers to define a number of specific studies that are needed to develop reliable tools for estimating how potential changes in man-made emissions would alter visibility. Toward that primary goal, EPRI is conducting studies with the following objectives.

- To establish a set of optical and aerosol measurement methods for obtaining data on various aspects of visibility
- To use these methods to survey the atmosphere at various locations in the eastern and western United States
- To provide data on emissions and source characterization
- To develop fundamentally sound models for relating simple visibility indexes (e.g., visual range) to human perception and to materials suspended in the atmosphere, as well as models for determining the contribution of utility emissions to total suspended particulate matter and to visibility alteration

Methods assessment

The primary objective of an initial EPRI project (RP862-15) was to compare four state-of-the-art methods for estimating visual range—human observation, teleradiometry, photography, and nephelometry—by making measurements daily for nine months (June 1979–February 1980) at two sites in rural Ohio and Pennsylvania. Although methods are available for estimating historical visibility trends and causes of visibility impairment, the project's final report (EA-3292) documents that all the instrumental methods for measuring visual range overestimated the prevailing visibility as determined by the human observer. Under ideal viewing conditions, the overestimation ranged from 25% to more than 100%. Under nonideal viewing conditions (e.g., clouds on the horizon, nonblack targets), none of the standard methods provided reliable estimates of visual range. Techniques for determining visual range reliably and consistently under these conditions must be developed.

Another project objective was to compare visual range values for the Ohio and Pennsylvania sites. The researchers found significant differences between the two; for example, the median prevailing visibility was 16 km in Ohio and 32 km in Pennsylvania. The results also underscore the differences in visibility between the eastern United States and the intermountain West, where visual ranges are typically much longer.

Still another project objective was to establish the association between visual range and aerosols. Data on total particulate matter by weight and on chemical composition for two particle size ranges were also obtained and are available for analysis.

Western monitoring program

EPRI's visibility research continued with a field program in the western United States, conducted under RP1630 as part of the Regional Air Quality Studies (RAQS). In this effort existing methods were adapted in order to make simultaneous optical and aerosol chemistry measurements. The adaptations were based in part on developments achieved in the eastern visibility study discussed above and the Sulfate Regional Experiment (EA-1901). The western field program was unique both in its measurement approach—aerosol sampling was conducted only during daylight hours and only when optical measurements were being made—and in the aerosol sampling system employed.

Figure 2 shows one of the program's sampling stations. It features a rotating dome for making optical measurements by contrast teleradiometry, nephelometry, and color photography and for human observation (following standard protocols) of such parameters as target distance, cloud cover, snow cover, fog, and rain. The tall structure on the roof next to the dome is the inlet to the aerosol sampling system. Because an atmospheric aerosol can be altered at sampling duct inlets, this structure is designed to let in only particles ≤15 μm in aerodynamic diameter. Inside the shelter four devices sampled aerosol from the duct: a nephelometer measured light scattering; two cyclone samplers collected particles ≤2.5 μm in diameter, one set for mass, ion, and elemental analyses and the other for carbon analysis; and one device collected two sets of particles by size (2.5–15 μm in diameter and ≤2.5 μm). The tower shown in the photograph was used for gathering wind velocity and humidity data.

After the monitoring approach and methods were developed and tested, a monitoring network was deployed (Figure 3) and two years of data were collected between July 1980 and October 1982. The purpose was to develop a data archive of specified precision and accuracy. Accuracy was established by calibration with traceable standards when available. Precision was established by continually testing the variability of crucial steps in the sampling and measurement process. The entire measurement process, from site sampling through data processing and archiving, was audited by an external quality assurance firm.

A preliminary integration of all the quality control test data indicates that for most of the aerosol components, the measurement uncertainty was about 10% of the median annual concentrations found in the rural intermountain West. A few of the chemical components, which were present at concen-

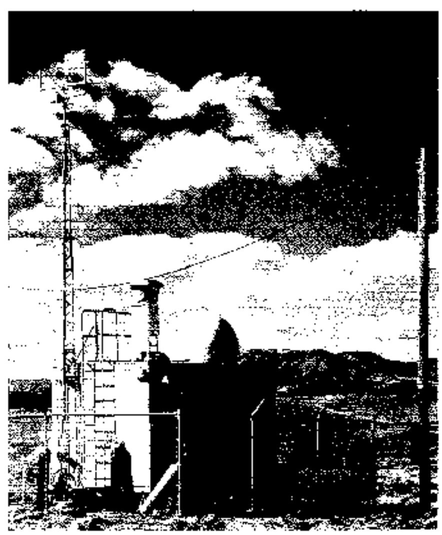


Figure 2 One of EPRI's visibility and aerosol observatories in the intermountain West. Visibility observations are made through a hatch in the rotating dome. Aerosol enters through the cylindrical hatted structure to the left of the dome and is sampled by instruments inside the shelter. The particulate matter collected on filters is sent to a central chemistry laboratory for analysis. The 10-m tower is used for obtaining meteorological data.

trations near their lower quantifiable levels, could be estimated only within 40–100% of the observed medians. The elements characteristic of wind-blown dusts (silicon and calcium) and of combustion and organics released to the atmosphere from natural and man-made sources (carbon) were measured within 25% of their median concentrations.

Although the aerosol and visibility data are still being consolidated and qualified in preparation for detailed analyses, some interesting findings about the composition of the aerosols are already emerging. Most of the particulate sulfur and carbon is contained in fine particles ($\leq 2.5\ \mu m$). It is surprising that often elemental and organic forms of carbon make up more of the fine particulate matter than do sulfates, and that most of the carbonaceous material is organic and not soot. For instance, on one clear day 51% of the light extinction was attributable to the sum of sulfates and carbonaceous material, with sulfates accounting for 20%. On one hazy day 75% of the light extinction was attributable to sulfur- and carbon-containing particles, with sulfates accounting for 33%. A puzzle to be solved in the continuing studies concerns the origin of the particulate organics.

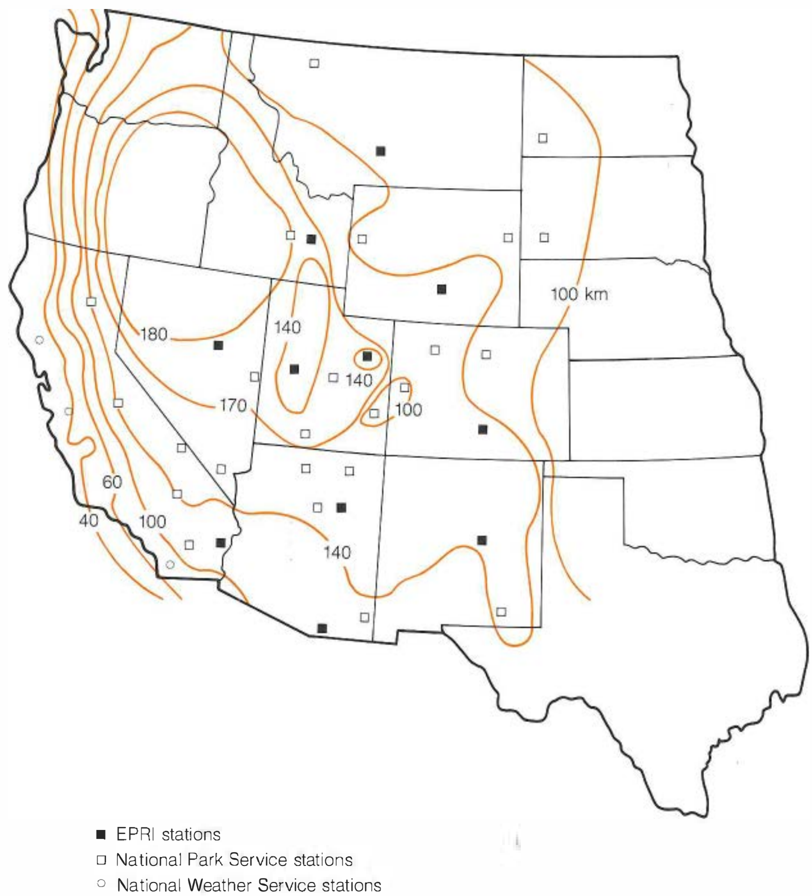
In comparison with the particulate measurements, the reliability of the visual range data is more difficult to quantify because they are influenced to a greater extent by the conditions of observation. According to the external quality audits, the act of taking measurements in the EPRI network was carried out virtually without error. However, the calculation of visual range values from the teleradiometric measurements involved more uncertainty. The accuracy of these calculations was assessed by viewing several targets located a similar distance from a station but in different directions. This assessment showed that depending on the viewing conditions, estimates of visual range varied by a few percent to as much as a factor of five. The most reliable estimates were made during periods when visual ranges like those shown in Figure 3 prevailed, and the least reliable estimates were made during episodes of low visibility—that is, those periods when the association with aerosols is most important for source attribution. The measurement data are currently being analyzed to determine if these uncertainties can be reduced by incorporating information about viewing conditions when deriving visual range from radiometric measurements.

Only through the reliable acquisition of teleradiometric measurements daily at many locations was EPRI able to recognize and evaluate the factors affecting the variability of the derived visual ranges. It turns out that the various groups making teleradiometric measurements are not using identical procedures. The determination of the most accurate procedure and its adoption as a standard method are among the major goals of EPRI's continuing cooperative visibility studies in the West. Standardization is very important for relating visibility to aerosols during episodic fluctuations. For estimating annual visibility medians, however, the uncertainties among networks appear to be quite tolerable.

The accuracy of deriving visual range from nephelometric measurements of light scattering is also a function of the environmental conditions under which the aerosol is sampled (e.g., humidity and temperature), as well as of the amount of light-absorbing material (e.g., soot) in the aerosol, which is not measured by the nephelometer. The influence of these factors and how to account for them in deriving visual range from nephelometric data are currently being evaluated. The main usefulness of nephelometric data is in linking the chemical and optical properties of an aerosol.

Although photographs are valuable as supplemental information in evaluating teleradiometric data, standard human observation of targets to establish visual range turned out to be virtually useless in the intermountain West. This is simply because the distances between targets available at most observatories are too great for making suffi-

Figure 3 To collect visibility data, EPRI operated 11 observatories in the intermountain West in 1980–1982. Horizon contrast measurements made at these stations and at National Park Service stations, together with observations of prevailing visibility made at National Weather Service stations, are the basis for the median visual ranges shown here (in km) by the isopleths. Visual ranges in the area are generally long, with pockets of lower values in Utah.



ciently precise estimates. Of course there are exceptions, and one of these sites is being used in comparing instrumented methods with human observation. In addition, EPRI is sponsoring fundamental research to establish systematically how the eye and brain respond to radiation (in various colors) from targets (RP2491). This research with observers is designed to establish, to the exclusion of psychological value judgments, the relationship between observations made with optical instruments and the human optical system.

The two-year data set from the EPRI western monitoring program serves as an important supplement to other visual range observations by teleradiometry in networks sponsored by local, state, and federal agencies. The annual averages agree closely for nearby sites, and some EPRI stations improved spatial resolution by providing data for areas where none had been available.

Southwest study

The western field program has provided baseline data for 11 locations so widely dispersed that each could be representative of a subregion. The sites were not deployed to study the origin and evolution of hazes in terms of space and time. To do so requires a subregional network. As part of EPRI's continuing RAQS effort, such a network has now been established in cooperation with utilities and federal agencies for a study called SCENES. In addition to EPRI the participants are the Salt River Project, Southern California Edison Co., the National Park Service, the Environmental Protection Agency (through its research laboratories in Las Vegas, Nevada, and Research Triangle Park, North Carolina), and the Department of Defense (through the environmental services staff at the Naval Weapons Center at China Lake, California).

The basic goal of SCENES is to determine the relative contributions of various emission sources to atmospheric optical properties in the desert Southwest. The study is expected to run for five years. The subregion being investigated encompasses the southern portions of California, Nevada, and Utah, along with northern and central Arizona. This area offers a desirable real-world experimental situation because man-made emission sources are located at relatively large distances along the various air mass trajectories that influence flows in and out of the Grand Canyon. It is hoped that SCENES will produce both a proven methodology for conducting visibility studies and the knowledge necessary to maintain visual air quality in the Southwest.

Emissions

Although the current major experimental focus of RAQS is field measurement, meeting the primary objectives of visibility research requires a detailed inventory of emissions, including wind-blown dust, man-made particulate emissions, natural organics, sulfur oxides, nitrogen oxides, man-made hydrocarbons, and ammonia. Such an inventory is now being prepared for North America (RP1630-23), and it will be used to support visibility and other air quality studies.

The current studies on emissions, while necessary, are not sufficient by themselves, however. It will also be necessary to characterize the major sources in greater detail with respect to the substances they emit and the physical properties of those substances. The feasibility of using such substances as tracers—or of releasing other tracer materials—to identify and quantify the relative contributions of various sources to atmospheric emissions is now being intensively studied with respect to several air quality applications, including visibility (RP2199). The results of that study, expected early in 1985, will guide the design of further studies on source characterization (RP1625).

Modeling

When the various factors that influence visibility are completely understood, it ought to be possible to devise mathematical and computerized schemes for reliably calculating answers to "what if" questions. These answers could then be used to make decisions about controlling anthropogenic emissions that contribute to visibility impairment. Modeling schemes now available for calculating the influence of air quality on visibility are being evaluated as part of RAQS. The current state of the art suffers from oversimplifications because of a lack of knowledge, a situation that EPRI's experimental field studies are designed to remedy.

The heart of EPRI's research on air quality modeling concerns the capability of calculating the fate of emissions from the time they leave a power plant stack to the time a fraction reaches a point of ground-based observation (receptor location). Three major modeling studies are under way that have relevance for visibility problems. One is the plume model validation and development project (RP1616), which has provided information on dispersion near the point of emission. The ability to calculate this dispersion accurately is an important first step toward simulating regional dispersion. EA-3047 summarizes the results of this study and lists the 18 other reports that document it. Supporting data on particle formation in plumes are reported in EA-3231 and EA-3105.

The second modeling study is an assessment of regional air quality models (RP1630-21). This study, expected to be completed this summer, is examining in detail three different calculation schemes that have been used in western and eastern North America to estimate the influence of power plant emissions on regional air quality, including visibility. This evaluation is addressing the fundamental assumptions underlying the mathematical equations, the accuracy of their representation in computer codes, and the adequacy of available observational data for testing model performance. Results on the last topic are influencing the design of SCENES and other field studies.

The third EPRI effort in this area is the receptor model feasibility study (RP2199). One of the major objectives of visibility research is to allocate to sources the materials in aerosols occurring at observatories. One approach for accomplishing this involves the application of source-oriented models. In another approach, called receptor modeling, the relative contributions of various sources are detected and quantified by "fingerprinting" the composition of the aerosol sampled at the observatory.

In previous applications the receptor approach, like the source approach, has been limited in accuracy and precision because of the use of simplifying assumptions. With this study EPRI hopes to establish what knowledge is needed to eliminate these oversimplifications and what measurement data are needed, both for sources and for receptors, to apply receptor models to utility emissions with tolerable accuracy. This study is expected to define the practical limitations of receptor models and to determine in what contexts they will be feasible. The results will be used to reexamine the suitability of visibility field study measurements for application in receptor models. *Project Manager: Peter K. Mueller*

R&D Status Report
ENERGY MANAGEMENT AND UTILIZATION DIVISION

Fritz Kalhammer, Vice President

CUSTOMER-SIDE BATTERY ENERGY STORAGE

Energy storage for load management is a venerable but currently underused concept. Thermal energy storage as a load management option for the residential customer's side of the meter has been a practice for many years in Europe, where electricity rate structures make it attractive. In the United States, however, rate structure has been a major factor in discouraging all forms of customer energy storage. Batteries, as a form of storage, have been especially handicapped by their high cost. Under the combined impact of high energy cost and power plant costs, utility interest is growing in load management by means of customer energy storage. To estimate the extent of customer interest, EPRI engaged Bechtel Group, Inc., to assess the viability of energy storage that uses conventional lead-acid batteries on the customer's side of the meter (RP1275-12).

A typical battery system consists of three major subsystems.

□ The battery, which encompasses the cells, racks, interconnecting dc wiring (up to but not including the dc bus), and all required accessories for the battery (e.g., flash arresters, watering valves, and air-lift pumps)

□ The power conditioner, which interfaces the dc output of the battery with the ac utility grid and includes all the equipment necessary for charging and discharging the battery in response to a control signal that sets the power level and the current direction

□ The balance of plant, which includes the structural, mechanical, and electrical support items required in the facility for full operation of the entire system

In concept the system is deceptively simple. The battery is charged during periods when electric energy is least expensive to the customer—usually in the early morning hours. The control system, which may be very sophisticated, then discharges the stored energy during a time period that will minimize the utility charge for electric power and/or the customer's energy use. Normally, this involves shaving the peak, which minimizes the demand charge. This demand charge and the cost of the components of the battery energy storage system, including maintenance and replacement costs, will dictate the economic feasibility of a customer-owned system. The Bechtel study based its results on state-of-the-art lead-acid batteries and other components; the technical and economic feasibility of advanced batteries for this application was not the primary focus.

Phase 1 of the study assayed economic viability by calculating the before-tax return on investment for a few representative installations. Bechtel contacted about 20 electric utilities having demand rates in excess of about $8/kW and asked these utilities to participate in the study by providing current rate schedules and the load profiles of customers having load peaks coincident with the utility's peak (those customers presumably subject to high demand billings). Five cases were then selected for detailed analysis.

Bechtel obtained data relative to the costs, performance, life, reliability, maintenance, and support equipment for the battery and power conditioner subsystems by contacting the major suppliers. For a given battery size (energy storage capacity at a specified rate of discharge), it used the load profiles and rate schedules to derive the savings that could be achieved by reduced demand billing. A proprietary computer program, written earlier by Bechtel, allowed a ready calculation of the before-tax rate of return (ROR). Sensitivity studies displayed the impact of variations in several input parameters on this ROR. A summary of the results of the feasibility study (detailed in EPRI EM-2769) follows.

□ Existing electric rate schedules and typical customer load profiles make customer-side energy storage a potentially viable load management option, yielding acceptable RORs.

□ The important nonhardware factors that affect economic viability are demand charge, discharge duration, and customer load profile shape.

□ Battery and power conditioner costs are the major cost factors among the hardware items.

□ The size of the battery has a smaller effect on the economics. At the time, balance-of-plant costs were thought to be secondary in effect; a later study revised these findings.

The study continued in Phase 2, which expanded on Phase 1 in two respects: a dozen additional cases were reported in detail, and a revised format for economic analysis yielded annual cash flows and after-tax return on investment, financial measures well understood by corporate financial officers. This phase used a more sophisticated (but still proprietary) computer program, also developed by Bechtel. EPRI published the results in a two-volume report early in 1984 (EM-3535). An appendix to the report conducts a sample calculation in detail so that interested parties can check the results. (Some of the Phase 2 results appear here in Table 1.)

To better understand the makeup and importance of balance-of-plant costs, EPRI initiated Phase 3 of the project in the fall of 1983. This phase of the contract with Bechtel consists of the conceptual design and analysis of balance-of-plant costs for a specific customer installation. A textile plant on a utility grid in the southeastern United States had the representative balance-of-plant requirements. The willingness of the electric utility and the manufacturer to participate in the study was a factor in their selection; the comparative return on investment did not figure in the choice.

Preliminary results suggest that the balance-of-plant costs make a larger contribution to the installed cost of the battery energy storage system than was earlier believed—a reduction of about five points in the typical ROR. This, however, does not alter the conclusion that customer-side battery energy storage is economically viable.

Table 1
ECONOMIC FEASIBILITY ANALYSIS
CUSTOMER-SIDE BATTERY ENERGY STORAGE

Application	Demand Charge ($/kW)	Battery Size (MWh ac)	Before-Tax ROR (%)	After-Tax ROR (%)	Payback (yr)
Railroad	16.24	5.6	66	—	2.2
Steel mill	11.88	2.3	45	33	3.5
Copper alloy smelter	13.50	0.7	38	28	3.5
Shipyard	11.36	1.5	31	25	4.6
Navy installation	8.71	5.0	28	—	4.3
Agricultural machinery	9.62	0.4	23	18	5.4

To physically demonstrate the viability of customer-side battery energy storage, EPRI purchased a 500-kW, 500-kWh lead-acid battery from GNB Batteries and installed it in the Battery Energy Storage Test (BEST) Facility (Figure 1). Early in 1984 tests of the battery began in the charge-discharge modes suggested by customer profiles obtained in Phase 2. After a few months of testing, EPRI will offer the battery and the associate converter (purchased from Firing Circuits, Inc.) to interested utility-customer teams for installation at the customer's site. (EPRI anticipates using the RFP process to select the team and the site.) At the end of the demonstration, customer-side battery energy storage should be thoroughly documented as a viable load management option for the electric utility industry. *Project Manager: David L. Douglas*

Figure 1 A 500-kW, 500-kWh lead-acid battery, installed in the Battery Energy Storage Test Facility, should demonstrate the feasibility of energy storage on the customer's side of the meter.

FIRST-GENERATION FUEL CELLS

The primary objective of EPRI's fuel cell research is to expedite the commercial introduction of first-generation phosphoric acid fuel cells for dispersed power plant applications. Using petroleum and coal-derived fuels in an environmentally acceptable manner, these power plants can achieve heat rates near 8000 Btu/kWh. EPRI's activities are part of a much larger, nationally funded effort to make first-generation fuel cells available for utility applications by the early 1990s. This report is an overview of the larger, nationally coordinated fuel cell development effort. Previous EPRI Journal *articles have discussed EPRI's fuel cell program (most recently, June 1983, p. 54).*

EPRI is supporting three major activities to expedite the commercial introduction of power plants that use first-generation phosphoric acid fuel cells. These activities, closely coordinated with activities supported by DOE, are part of an aggressive national effort that includes five major elements.

▫ Installing and operating a 4.5-MW net ac fuel cell module on the system of Consolidated Edison Co. of New York, Inc. (RP842). EPRI, DOE, United Technologies Corp. (UTC), and a group of utilities led by Con Edison are sponsoring this user-oriented effort, which will demonstrate that utility personnel can site, install, operate, and maintain fuel cells; that dispersed fuel cell generators offer benefits to utility systems; and that the technology is technically ready for first-generation commercial applications.

▫ Upgrading the 4.5-MW UTC demonstrator design to a configuration more commercially viable for utility applications (RP1777). EPRI, Niagara Mohawk Power Corp., and Northeast Utilities are sponsoring efforts to reduce capital costs and to improve plant reliability, maintainability, and durability. These efforts include development and verification tests of fuel processing and other key plant components.

▫ Developing fuel cell technology, manufacturing techniques, and scale-up of components (RP1200). DOE, with minor support from EPRI, is sponsoring development that will enable UTC to manufacture 10-ft² (0.9-m²) fuel cell components, which are larger than the 3.7-ft² (0.3-m²) components used in the 4.5-MW demonstrator. This effort is attempting to establish manufacturing repeatability and to verify fuel cell performance and endurance, while reducing the specific cost of the fuel cell stack by roughly 50%. DOE is also supporting similar work at Westinghouse Electric Corp. to develop its air-cooled fuel cell technology.

▫ Defining a Westinghouse air-cooled 7.5-MW gross dc power plant (RP2192). EPRI is sponsoring this technical effort in coordination with DOE's technology development effort. The EPRI scope includes definition of power plant and system design requirements, as well as development and verification of the plant's fuel processing system.

▫ Transferring technology from fuel cell developers to utility users. The Fuel Cell Users Group, comprising 55 utility members, is playing an important role in this effort. By reviewing performance specifications and design documentation, the group has helped UTC and Westinghouse to focus their development efforts on a product that is attractive to the utility industry. Present activities should stimulate fuel cell commercialization by identifying early and follow-on purchasers of fuel cell power plants.

Demonstration plants

The 4.5-MW fuel cell power plant at Con Edison continues to be a challenging, first-of-a-kind demonstration project. Major accomplishments last year included operation and verification of the power plant's process and control (PAC) system and its power conditioning system (PCS), as well as installation of the fuel cell power section modules.

During the PAC tests, the plant's fuel supply, fuel processing, air supply, steam, and water treatment systems operated in a stable and integrated fashion. The plant processed naphtha fuel at a rate equivalent to 25% load into a hydrogen-rich process gas that subsequently was flared to the atmosphere (the fuel cell power sections had not yet been installed). During the checkout of the PCS, the dc-to-ac inverter and PCS electronics operated for 100 h at 4.5 MVAR while connected to the Con Edison grid. The PCS checkout tests demonstrated stable operation and compatibility with fluctuations on the utility grid.

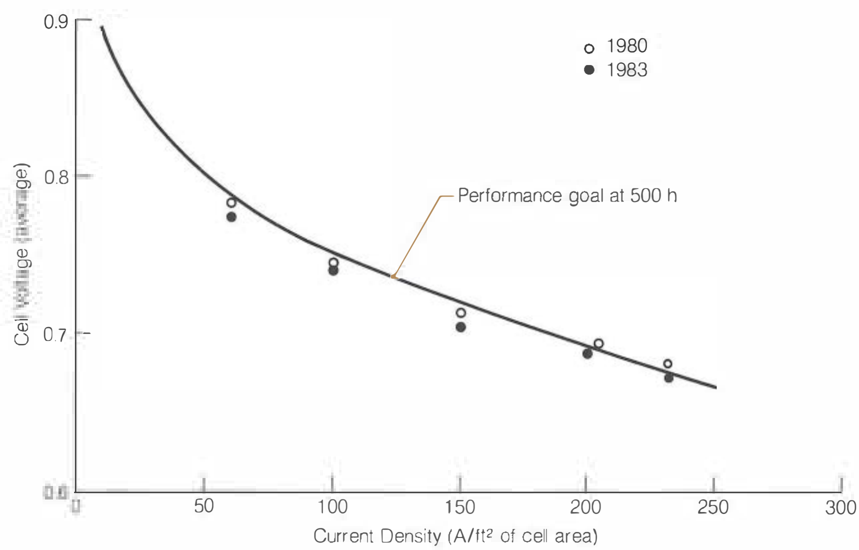
The two fuel cell power section pallets were delivered, installed, and prepared for power operation at Con Edison during the last quarter of 1983. Also during this period, workers upgraded the water treatment system and associated piping to meet revised fuel cell water quality specifications. With all site work completed by December 19, researchers scheduled the plant validation and acceptance tests to begin the first week in January 1984. However, a water leak in one of the 20 fuel cell stack assemblies (CSAs) delayed plant startup until the CSA was removed from service and replaced. The remaining CSAs and the two spares appear to be suitable for power generation, which is expected to begin this spring. The age and condition of the CSAs, however, have required UTC, Con Edison, DOE, and EPRI to reconsider options for the future role of this facility. Extended plant operation is no longer a necessity because of the successful operation of a similar (but newer) 4.5-MW unit by Tokyo Electric Power Co. (Tepco) in Japan.

It is important to note that the CSA configuration used in the Con Edison unit is an obsolete design. The Tepco power plant employs a new CSA configuration (developed under RP114 and RP842) that has virtually unlimited storage life.

EPRI supported a retest of a 250-kW stack in 1983 that had been built and tested in 1980 under the sponsorship of the Tennessee Valley Authority. At that time the stack was operated as "proof of principle" of the CSA configuration that was to be used in the Tepco plant. This CSA design overcomes the phosphoric acid loss that had contributed to the storage and endurance problems known to be inherent in the Con Edison 4.5-MW plant. Test results shown in Figure 2 are most encouraging: researchers found absolutely no difference in performance after three years of storage. UTC's present CSA development and fabrication activities are based on this configuration.

Progress at the Tepco 4.5-MW power plant is also quite encouraging. (EPRI and DOE are not involved in the Tokyo project.) As of March 22, 1984, the plant had operated in the power generation mode for a total of 196 h (370 MWh). A maximum output of 4.5 MW ac was achieved early in 1984, and the measured heat rate was ~9400 Btu/kWh, within 1% of UTC's estimated value for this power level. The power plant's steam-methane reformer has undergone 120 thermal cycles with no change in performance. Tepco reported that all measured operating parameters were stable and within predicted values. Tepco has also stated that it plans to operate and run the 4.5-MW demonstrator for an endurance test during the remainder of 1984, which will enable UTC to gain further design and calibration data needed for its commercial fuel cell plant design efforts.

Figure 2 The performance of UTC's 250-kW CSA was unchanged after three years of storage, thus confirming that this advanced fuel cell configuration is viable for utility applications.



Commercial fuel cell system design

EPRI funding and user group input have helped UTC to define a commercially viable fuel cell system that is considerably less complex than the 4.5-MW demonstrator. EPRI has published a detailed description of UTC's generic 11-MW fuel cell power plant to enable utilities to better understand the characteristics, design, and installation requirements of a fuel cell plant (EPRI EM-3161).

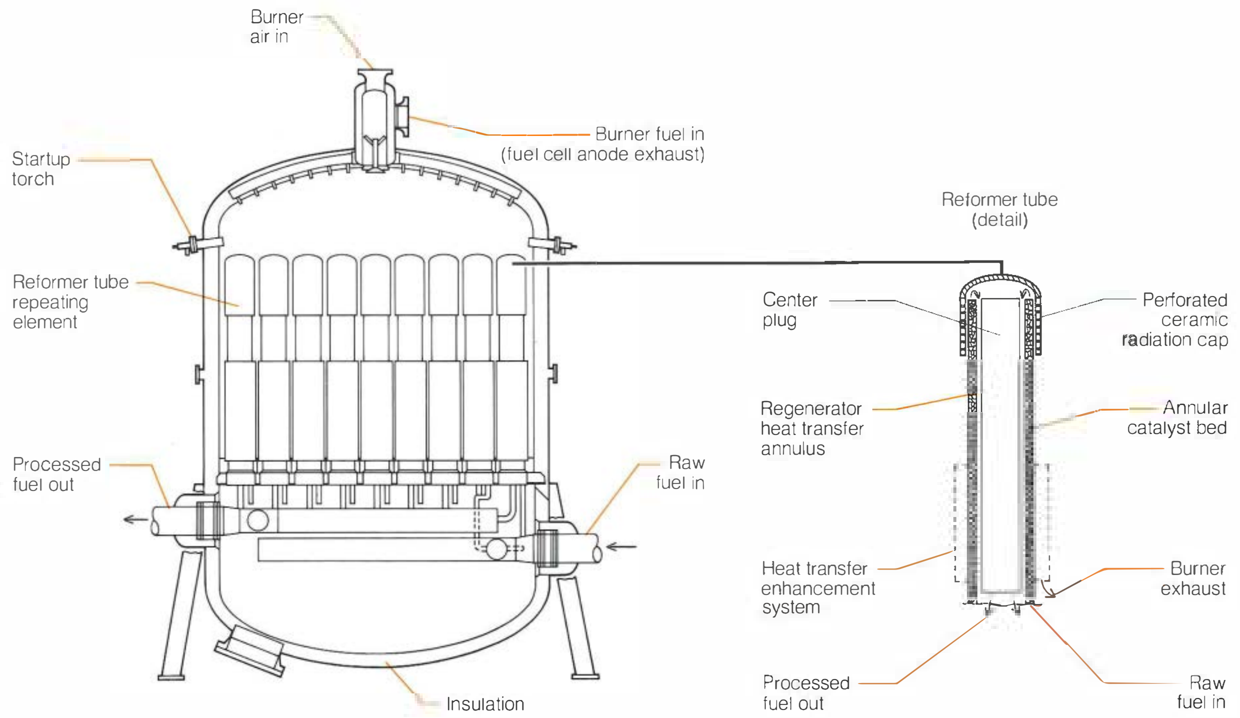
Many of the 11-MW plant characteristics, such as its 8300 Btu/kWh heat rate, 4-h startup, cycling capability, fast-transient response, and transportability by truck, impose significant design challenges on the power plant's fuel processing system and, in particular, on the catalytic steam reformer. During the past two years, EPRI has sponsored the development and verification of UTC's steam reformer design, shown in Figure 3 (RP1777).

UTC's reformer has several novel aspects.

- Pressurized furnace at 120 psia (827 kPa) to improve overall power plant integration (e.g., heat rate) and to promote convective heat transfer
- Annular reformer tube configuration to provide internal regeneration (thus reducing furnace firing duty and heat rate), to improve transient response because of a higher ratio of heat transfer surface area to catalyst volume, and to minimize the crushing of catalyst during thermal cycling
- Convective heat transfer (in contrast with the predominantly radiant heat transfer in conventional reformers) to reduce furnace firing duty and to provide for a more closely packaged tube assembly that can be transported by truck

Sponsored by EPRI, Niagara Mohawk, and Northeast Utilities, verification testing of this full-scale repeating element (operating at 11-MW process and burner firing conditions) demonstrated the performance, efficiency, and durability of UTC's design. The present repeating element configuration has operated successfully for over 1620 h and 27 thermal cycles. EPRI's support in this area is continuing in 1984, with emphasis on multi-

Figure 3 The conceptual 11-MW steam reformer consists of three truck-transportable pieces; when assembled, the 23 × 13-ft-diam (7 × 4-m) vessel weighs ~112,000 lb (50.8 t). The UTC design consists of 60 repeating tube elements measuring ~90 × 11-in-diam (230 × 28 cm). Tests of a full-scale repeating element have demonstrated performance and durability.



megawatt reformer burner design, performance, and durability.

Fuel cell technology development

DOE has taken the lead in sponsoring the development of fuel cell stack technology to meet utility power plant performance and cost requirements. Although DOE is funding both UTC and Westinghouse in these areas, the UTC technology has progressed sufficiently to highlight its achievements here.

UTC has demonstrated that its advanced 3.7-ft² (0.3-m²) phosphoric acid fuel cells are technically viable. Short stacks consisting of 20–30 cells (~20 kW) have operated for over 10,000 h in the laboratory at 11-MW system conditions. In addition, similar full-size stack modules (250 kW each) have operated successfully in the field at the 4.5-MW Tepco site under actual power plant conditions. Performance and endurance results are encouraging, indicating that power plant heat rates near 8000 Btu/kWh are achievable in early prototype units and stack life may be longer than initially expected.

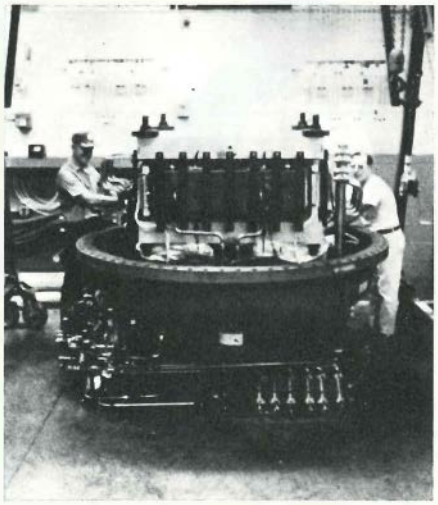


Figure 4 UTC's first 10-ft² short stack, mounted in its pressure vessel, is the largest fuel cell component ever made. Each of the 30 cells, operating at 120 psia (827 kPa) and 405°F (205°C), delivers 0.73 V. The full-size stack in the 11-MW system will consist of ~500 cells, will deliver ~675 kW, and will be contained in a 13 × 6-ft-diam (4 × 1.8-m) pressure vessel.

The present challenge is to manufacture and assemble the larger 10-ft² (0.9-m²) fuel cell components required for the 11-MW system and to reduce their manufactured cost by roughly 50%. UTC has made considerable progress scaling up the 3.7-ft² (0.3-m²) hardware. It assembled the first high-pressure (120 psia; 827 kPa) 10-ft² short stack and began testing in 1983 (Figure 4).

DOE's support of the UTC effort will continue in 1984. Short (3.7-ft²) stacks will continue to be endurance-tested up to 20,000 h, if possible. UTC will also manufacture, assemble, and endurance-test large 10-ft² components. Cost reduction improvements will be monitored to ensure that first-generation fuel cells are commercially competitive with other dispersed power generation options.

The DOE- and EPRI-coordinated efforts complement the UTC commercialization strategy, which calls for the offering of one or more 11-MW prototype units in 1984. *Project Manager: D. M. Rastler*

R&D Status Report
NUCLEAR POWER DIVISION

John J. Taylor, Vice President

INFLUENCE OF BWR CHEMISTRY ON PIPE CRACKING

*Intergranular stress corrosion cracking (IGSCC) of sensitized austenitic stainless steel has been the major environment-related materials performance problem in boiling water reactor (BWR) coolant systems. Over the last 10 years more than 400 cases of IGSCC in sensitized material adjacent to welds in types 304 and 316 stainless steel pipes have been reported. Although these cracks are not considered a safety problem, inspections and repairs are expensive, and the industry has undertaken substantial research to understand the IGSCC phenomenon and remedy its occurrence. Much of the early research focused on alternative materials or local stress reduction, but recently EPRI, BWR Owners Group, and NRC have turned their attention to the effects of water chemistry on the IGSCC process. Researchers do not completely understand the interrelationship between BWR water chemistry variables and IGSCC, but they have identified some important features (*EPRI Journal, *January/February 1983, p. 52). The objective of current EPRI research on BWR water chemistry is to determine the effects of impurities on IGSCC so that the industry can formulate water quality guidelines to minimize pipe cracking.*

The effect of water on stainless steel is relatively small, even at the high temperatures required for electricity generation. However, radiolysis products and impurities can make water aggressive toward stainless steel and create an environment that promotes IGSCC. During normal operation, radiolysis decomposes small amounts of the pure water in the BWR core into free oxygen and hydrogen, trace amounts of which remain dissolved in the reactor water. Ionic impurities (salts) seep into the water from such sources as makeup water and condenser leaks and are controlled by condensate and reactor water cleanup systems.

Impurities that exacerbate pipe cracking fall into two categories, depending on their action. The oxidizers, represented by the dissolved oxygen, enhance the chemical environment in which the corrosion reactions take place. The ionic impurities, such as chloride ions, can increase the rates of corrosion reactions by raising the water's electrical conductivity and creating a chemically aggressive environment. Figure 1 represents current thinking about the effects of oxidizers and ionic impurities on SCC.

EPRI is currently studying these effects. One project is investigating oxygen control by hydrogen water chemistry (RP1930). Other projects are quantifying the effects of impurities other than oxygen on SCC.

Hydrogen water chemistry

A possible method of decreasing the oxygen concentration in BWR water to levels well below the normal 200 ppb is by injecting hydrogen into the feedwater. This method is called hydrogen water chemistry, or H_2WC. The presence of hydrogen suppresses oxygen formation by radiolysis of core water. The effectiveness of this approach has been demonstrated in two short-term experiments in a Swedish BWR and more recently in Commonwealth Edison Co.'s Dresden-2 reactor in a project funded by DOE, EPRI, and Commonwealth Edison.

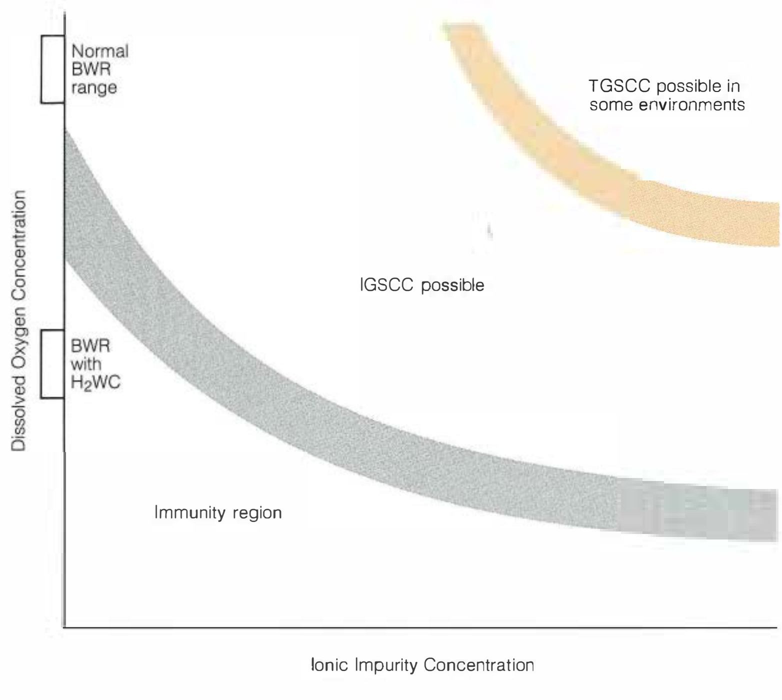


Figure 1 Effect of impurities on stainless steel SCC in high-temperature water. As the concentration of dissolved oxygen or ionic impurities increases, austenitic stainless steel's susceptibility to SCC increases. At very low concentrations, the material is immune to SCC. Above the gray region, IGSCC of sensitized material can occur, and the rate of cracking increases as the concentration increases. At even higher concentrations (above the color region), transgranular stress corrosion cracking (TGSCC) of annealed material can also occur if certain impurities (e.g., chloride) are present. Brackets show the ranges of dissolved oxygen in normal BWR water and in reactors operating with the experimental hydrogen water chemistry.

Researchers also studied the phenomenon in the laboratory (RP1930-1). These studies indicate that the H_2WC environment is more innocuous than the normal environment for most plant materials. An interim report, which details the results of the laboratory experiments, is forthcoming.

Although the Dresden-2 project demonstrated that controlling oxygen by means of hydrogen is feasible for a U.S.-type BWR, the duration of the experiment (1 month) was insufficient to obtain any significant information on possible long-term benefits or adverse effects of adding hydrogen. Therefore, EPRI is funding a longer-term H_2WC study at Dresden-2.

The new project will investigate the effects of operating a BWR with H_2WC for at least two fuel cycles (36 months). Commonwealth Edison is the host utility for the in-plant work at Dresden-2, which is being performed under RP1930-9. In addition to the effects of H_2WC on plant materials studied in RP1930-1, other factors under investigation include radiation buildup, crud deposition, fuel-cladding corrosion, and nitrogen-16 control. General Electric Co. is the contractor for RP1930-7 and RP1930-10, and Advanced Process Technology Co. for RP1930-8.

The long-term Dresden-2 project began in April 1983. The first fuel cycle (about 18 months) should provide enough information to determine whether H_2WC can be recommended for other U.S. BWRs. Continuation of this project should warn of any unanticipated negative effects that might develop as a result of the long-term use of the new water chemistry.

Effects of impurities

The influence of other impurities in BWR water has been less well studied. Indications are that ionic impurities can couple with oxygen to promote IGSCC and that certain species are more deleterious than others. Researchers have investigated the effects of impurities on SCC in the laboratory (NP-3384, NP-3174-LD). Additional studies are in progress at Ohio State University's Fontana Corrosion Center (RP1166-1). Research conducted under RP1563-2 showed that resin in the water can also promote IGSCC (NP-3145). Organic substances may be present in reactor water as a result of resin degradation or from other sources, and the effects of organic impurities on the SCC of materials is currently unknown.

EPRI has initiated a three-year effort to study the effects of water impurities on BWR plant materials (RP2293). The objectives are to identify the impurities that promote SCC and to formulate water quality control guidelines. An EPRI project with ASEA-Atom will identify the most harmful impurities by conducting laboratory stress corrosion and corrosion fatigue tests (RP2293-1). This study will emphasize stainless steel IGSCC but will also investigate corrosion cracking in other BWR structural materials.

In a separate project, General Electric will determine the effects of impurities in BWRs. The study will use sophisticated chemical techniques to quantify each of the impurities currently present in the reactor water of Philadelphia Electric Co.'s Peach Bottom-2 reactor (RP1447-1). Simultaneously, in-plant tests will determine the susceptibility of several BWR structural materials to SCC and the pathways by which these impurities enter the reactor water (RP2293-2). Figure 2 shows possible pathways for various impurities. Once in the water, these substances may be converted into other, more harmful impurities as they flow through the core.

After initial tests, the plant operation will be changed to close off the pathways and decrease impurity levels. Then researchers will repeat the SCC testing and water quality analyses to determine the benefits of water quality improvements. This information will be incorporated into BWR water chemistry guidelines to help plant operators minimize pipe cracking and other BWR corrosion problems. *Project Managers: Robin Jones and Daniel Cubicciotti*

EXTENDING BWR FUEL CHANNEL BOX LIFE

Channel boxes of Zircaloy-4 enclose the entire length of boiling water reactor (BWR) fuel assemblies. The boxes are designed to distribute the reactor coolant among the fuel assemblies. The channel boxes also support the fuel assembly and allow unrestricted motion to the control blades in the bypass regions created by adjacent channels. During operation, radiation exposure and pressure differences across channel box walls cause the boxes to deform. Because deformed boxes can interfere with control components, deformation limits determine how much deformation a box can sustain before it must be removed from service. Current practice requires that channel boxes be discharged with the fuel assembly. EPRI research suggests that in most cases this criterion is very conservative and that extending channel box life for use on two consecutive fuel assemblies may be possible.

In the active regions of BWR fuel bundles, heat is transferred from the fuel rods directly to the coolant, which then boils. No boiling

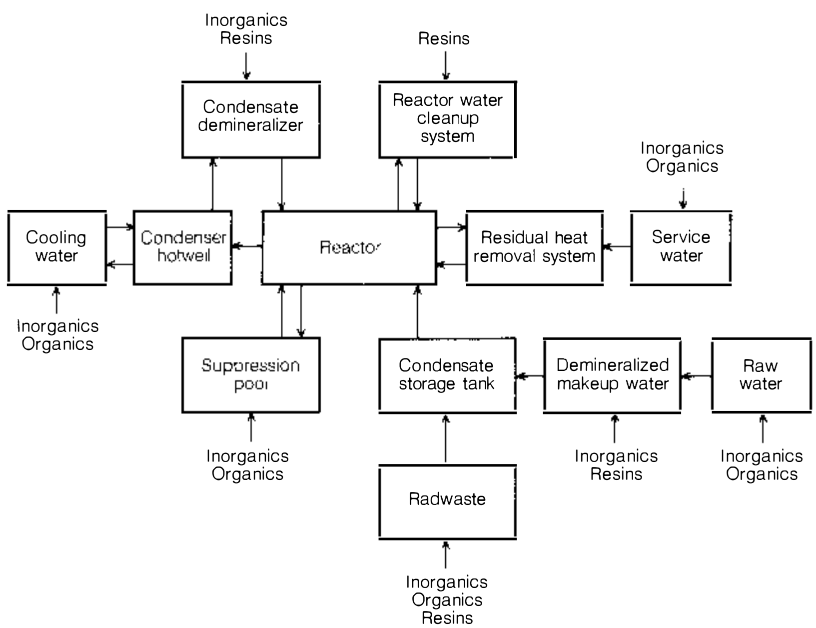


Figure 2 Potential impurity pathways into BWR water. Impurities can enter the reactor water from a number of systems. The figure shows which types of impurities gain access to the water through particular systems. (Inorganics are saltlike chemicals; organics include such substances as lubricating oils, soaps, and algae; resins are polymeric materials used to demineralize water.)

takes place in the bypass region. The channel box separates the two flow streams and physically prevents their mixing (Figure 3). During operation fuel channels are exposed to radiation fields that cause changes in the Zircaloy box structure. As a result, the Zircaloy grows with the amount of time the material spends in the reactor. Because the alloy is not isotropic, growth occurs in particular directions defined by its crystal structure and fabrication parameters. The radiation flux is not uniform on all box faces, so opposite sides of a channel box may grow at different rates and cause it to bow. Bowing can be aggravated if the Zircaloy texture is not uniform throughout the channel box. This phenomenon can occur in channel boxes manufactured from two halves that have not been similarly processed.

Channel boxes also bulge outward because of greater coolant pressure inside the fuel channel than outside. (This difference is greater at the bottom of the box than it is at the top.) The combined bulge and bow determine the space between adjacent channel boxes and the extent of their interaction with control blades and instrumentation in the core's bypass regions.

Channel boxes corrode because radiolytic products and water impurities make the coolant chemically aggressive. Excessive corrosion films and nodules decrease the strength of the Zircaloy sheets, increasing their susceptibility to deformation under stress. In addition, zirconium oxide particles can lift off box surfaces and migrate to other parts of the reactor system, causing excessive wear in moving components. However, excessive corrosion and oxide spalling have occurred only in very few channel boxes to date because current designs offer adequate margin to at least five irradiation cycles.

Conservative guidelines govern channel box service life, and under RP1943-1 EPRI is determining whether this life can be extended from the present four years to as much as eight years (i.e., whether the box can serve two full assemblies). At the end of one fuel assembly lifetime, channels could be dismounted and the boxes installed on a fresh fuel assembly for continued use. This practice could reduce channel box replacement costs, which include procurement of new components and disposal of old ones.

The research plan consists of three parts. The first phase identified factors that define channel life-limiting conditions. For current designs, researchers found that channel deformation (bulging and bowing) toward a control blade was the most limiting restriction to continued use. They reviewed existing channel performance data and determined that channel boxes not fabricated from a single Zircaloy-4 sheet (i.e., unmatched halves of different texture) bow at a significantly higher rate than many boxes with matched halves. Such channel boxes are no longer used.

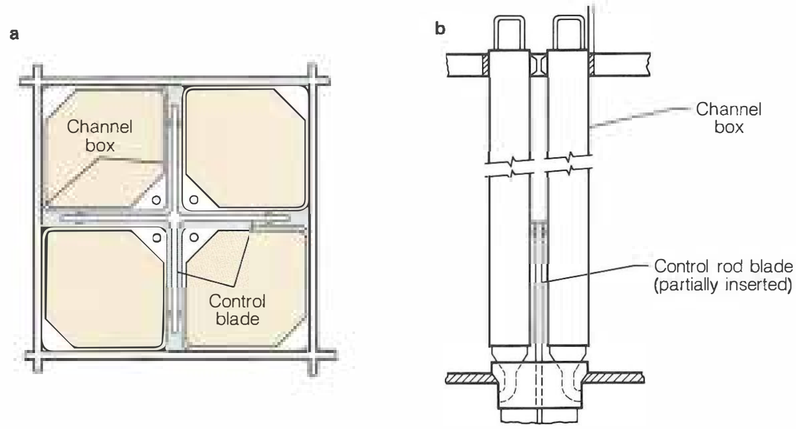


Figure 3 A channel box encases the fuel assembly. (**a**) The top view of a four-bundle control rod cell shows how the box prevents the boiling coolant (color) inside from mixing with the nonboiling coolant (gray) in the bypass regions. (**b**) The side view shows how the control blade moves along the length of the channel in the space created by four adjacent boxes. During operation, the boxes deform outward and interfere with control blade movement.

The bow of channel boxes of uniform texture can be predicted on the basis of their location in the core, which reflects the flux gradient across the channel. Channel boxes at the core's periphery are subject to large radiation flux gradients and tend to bow more than mid-core boxes. Residence times of more than one reactor operating cycle in peripheral core locations can reduce channel box life significantly.

Proper planning can control channel deformation by assigning boxes to specific core locations during each reactor cycle. Further, current limits are conservative because they assume that all channels in a control cell are interacting equally with the control blades. By shuffling boxes so that the interaction is restricted to a single wing of the blade, greater deformation can be accommodated without impairing control blade movement.

To shuffle channels a utility has to measure component deformation. Predictive models can reduce measurement requirements. Phases 2 and 3 of this project are developing such models.

In the second phase, researchers are collecting deformation data on in-reactor residence times and correlating them with various parameters that define operating conditions, including burnup and flux gradients and the history of pressure drops across channel walls. In the third phase, a greater body of data will be collected from utilities in the United States and other countries to improve the statistical correlation developed in the second phase. The objective is to supply utilities with models for predicting channel deformation that are simple to use and can be upgraded easily, depending on the specific requirements. The current plan is to complete model development by December 1984.

Channels of current design (i.e., channels of uniform texture) may be used for more than one fuel bundle. Improved channel management techniques and current deformation limits may allow a significant number of the components to be used for up to two fuel assemblies. An even greater number of channel boxes could meet this service life goal with new deformation limits.

At one utility, application of the EPRI results has reduced channel replacement costs 50%, or about $371,000 a cycle per BWR unit, in addition to lowering waste disposal costs. Additional savings can be expected as more channel boxes are reused.

The results available to date on the second and third phases confirm that many channels can be used for two fuel bundle lifetimes. EPRI will continue to study these components as they reach the end of their service life. *Project Manager: Joseph Santucci*

SOURCE-TERM TECHNOLOGY: RADIONUCLIDE REMOVAL BY POOL SCRUBBING

In many severe core damage accident scenarios, the steam-hydrogen mixtures (with entrained fission products) leaving the degraded core region and passing through the primary coolant system will pass through liquid water. In assessing the consequences of postulated nuclear reactor accidents, NRC's Reactor Safety Study *(WASH-1400) assumed source term values in the absence of experimental data. Current literature suggests, however, that decontamination factors (DFs) higher than 100 for subcooled (not boiling) water pools and 1 for steam-saturated (boiling) water pools, as postulated in WASH-1400, are possible. (DF is defined here as the mass of fission products entering the water pool divided by the mass of fission products leaving the water pool.) Larger DFs would significantly reduce the estimated consequences of a number of severe accidents postulated in probabilistic risk assessments. NRC is currently reassessing the source term, and EPRI is conducting limited full-scale pool-scrubbing experiments to measure DFs for a range of representative conditions. The EPRI test data and a computer model may play key roles in determining the new source terms.*

Before 1981 the experimental data base on retention of radionuclides by water pools—collected in laboratory-scale experiments—was limited primarily to elemental iodine and small volumes of unsaturated water. General Electric Co. conducted the first set of larger experiments in 1981, and in 1982 EPRI began a series of pool-scrubbing experiments (RP2117). The EPRI objective is to measure the removal of fission-product aerosols and validate models of steam-noncondensable mixture blowdown through the subcooled and saturated water pools that are typical of BWR suppression pools and PWR quench tanks under representative severe accident conditions.

The experimental project has three phases: single-orifice experiments, tests on multiple-orifice configurations, and downcomer and vent configurations. Each phase has both hydrodynamic tests and pool-scrubbing tests with fission-product aerosols. The hydrodynamic tests have been completed, and a report on the hydrodynamic tests of the first two phases is being revised.

Researchers have also completed the Phase 1 scrubbing tests. The current tests, data analyses, and reports are scheduled for completion in 1984.

Pool-scrubbing experiments

The tests were conducted in two tanks. One was 6 ft (1.8 m) in diameter and 8 ft (2.4 m) high; the other was 10 ft (3 m) in diameter and 16 ft (4.9 m) high. The hydrodynamic tests measured bubble size distribution, rise velocity, bubble column radius, and bubble number density at various pool elevations. The tests to date show no dependence of injected air flow rate on mean bubble size distribution for flow rates of 0 to 6 g/s. The bubble size distribution is the "stable" distribution achieved after the blown bubble globule has risen about 10 orifice diameters in the water pool. The angle of the injected gas stream did not affect the mean bubble diameter of the stable distribution. The mean bubble diameter is unchanging with depth of the pool; however, the distribution broadens as it rises in the water, resulting in an increasing standard deviation about the mean bubble size.

Injector diameter, gas molecular weight, and pool subcooling also did not affect the mean bubble diameter of the stable distribution. The only major factor that did affect distribution was the mass fraction of steam present in the injected gas stream.

In the multiple-orifice configuration, hydrodynamic tests showed that the initial gas globule growth and release from the injector depend on hole size, hole spacing, and flow rate. In the hydrodynamic tests a bubble's actual lifetime is short (a fraction of a second) because the bubbles continue to coalesce and break up.

The scrubbing experiments used one of three aerosols: cesium iodide, tellurium, or tin oxide. The aerosol was made in an aerosol generator and injected into a steam and noncondensable flow stream, which was then injected into the water pool in one of the two tanks. Researchers measured the amount of aerosol in the injection stream, in the water pool, and in the atmosphere above the pool and then determined a mass balance. In selected tests the aerosol particle size distribution was measured for the aerosol contained in the pool compartment atmosphere. The injection stream aerosol particle size distribution was measured, a very difficult task for cases in which the steam content is high.

The scrubbing test parameters included injector submergence, injection velocity (or mass flow), aerosol particle size, aerosol type (hydroscopic or nonhydroscopic), noncondensable gas (air, helium), steam mass fraction, pool temperature (subcooled or saturated), and injection geometry (single-orifice, multiple-orifice, downcomers, and horizontal side vents).

The Phase 1 single-orifice scrubbing tests in a subcooled pool show that steam mass fraction and aerosol particle size are the most sensitive parameters (Figure 4). The injection mass flow (or injection velocity) and submergence appear to show little effect on DF for the range of variation investigated to date. Researchers expect these parameters to affect DF more in the Phase 2 scrubbing tests, which will be done in the deeper tank and will indicate better the dependence of DF on pool residence time. Measured DFs have ranged from 1.5 to 8000, depending on test conditions.

The hot (saturated) pool tests produced some surprising results. The first hot-pool tests resulted in higher DFs than those measured in the subcooled tests, which was the reverse of what the researchers expected. In reviewing the test results, the project team discovered a synergism between the hot pool and the structure (pool compartment walls and ceiling). The steaming pool fostered condensation on the surfaces of the pool compartment and enhanced the decontamination. This phenomenon emphasizes

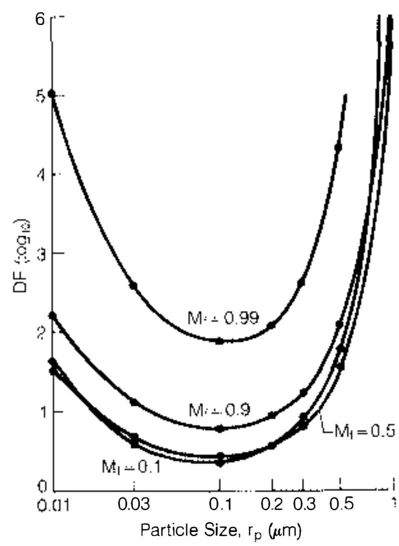


Figure 4 EPRI's pool-scrubbing computer code SUPRA was used to calculate the effect of particle size and mass fraction of steam on DF. The case calculated was for a pool 3.5 m (11.5 ft) deep at 300 K (81°F). A steam-hydrogen mixture was assumed with varying mass fractions of steam (M_f), a mixture temperature of 600 K (620°F), and an injected mass flow of 1.5 kg/s (3.3 lb/s). Note that the ordinate is the log of DF and represents the exponent of the power of 10, ranging from 0 (a DF of 1) to 6 (a DF of 10^6).

the importance of the physical conditions in the volume above the pool and of the temperature of the structures in that volume.

To understand the hot-pool test results, researchers installed a trough on one quarter of the tank circumference, just above the waterline. During a half-hour test with 95% steam, 2 L (about 2 qt) of condensate collected in the trough. This condensate contained significant amounts of cesium iodide, which had been injected as aerosol with the gas stream. Fission-product aerosol can condense on the compartment's vertical walls and drip into the pool. In an accident, however, the fission products that condense and run back into the pool are not likely to move into the environment.

To isolate the hot-pool phenomena, researchers recently ran tests with heated and insulated walls and ceiling in the smaller tank. These results, just becoming available, show significant DFs and for some conditions higher DFs than those in similar subcooled pool tests.

The majority of the pool-scrubbing tests were done with aerosols having a mass mean diameter of ~0.25 μm. The aerosol generator provides cesium iodide particles of this diameter, which coincidentally produces the minimum decontamination of all possible particle sizes.

The effect of aerosol particle size is understood theoretically. Hypothetical severe-accident conditions are likely to produce even higher DFs because a number of mechanisms cause agglomeration (particle growth). Although delay in the primary coolant system varies, it is usually long enough to increase the aerosol mean particle sizes, which will result in significantly higher decontamination in the pool.

Pool-scrubbing models

In addition to the experiments, EPRI has developed a computer code (SUPRA) that describes the scrubbing of fission products in water pools. SUPRA divides the scrubbing analysis into four zones. The injection zone describes bubble (or, more properly, globule) formation and breakup. The midpool bubble rise zone models the condensing or evaporating of steam and noncondensable bubbles. The pool surface zone treats desorption and evaporation from the pool surface along with entrainment of liquid droplets. Influenced by the discoveries in the experimental program, the model developers added a containment compartment to model the removal and dilution of aerosols and wall condensation.

The SUPRA model calculates time-dependent DF, pool conditions, and containment atmosphere conditions on the basis of time-dependent input of appropriate boundary conditions. Code aerosol removal mechanisms are sedimentation, Brownian diffusion, thermophoresis, diffusiophoresis, convective deposition, and inertial deposition.

SUPRA calculates time-dependent mass, energy, and material balances. Code validation has begun with the subcooled-pool experimental results. Figure 5 shows a plot of calculated and experimental DF values for a subset of EPRI experiments selected because the experimental analysis of the data is complete. The cesium iodide aerosol is estimated to consist of particles with a radius of 0.1–0.15 μm; these are the hardest to scrub, according to theory, because they are close to the minimum of the curve of Figure 4.

The gray lines in Figure 5 represent a factor of 2 higher and lower than the exact correspondence between calculation and experiment. When the project began in early 1982, some risk assessment experts indicated that calculations within a factor of 100 could be considered satisfactory. EPRI researchers determined that a factor of 10 was achievable. Today, pool-scrubbing DFs to within a factor of 2 appear realistic. This uncertainty is small compared with the uncertainty in calculating the core degradation process and the transport and decontamination throughout the rest of the nuclear system. As a result, the EPRI source term technology group will not try to further refine the pool-scrubbing decontamination calculations but, rather, will seek to understand the phenomena that contribute other, larger uncertainties in determining the source term.

Continuing efforts

EPRI is fostering information exchange among representatives of NRC, contractors, consultants, and vendors. Some EPRI utility members have sent representatives to information exchange meetings; members who find that pool scrubbing is of interest are welcome to attend future meetings. The goal is to provide technical data for NRC's source term determination to ensure as realistic and technically defensible source term as possible. *Project Manager: R. N. Oehlberg*

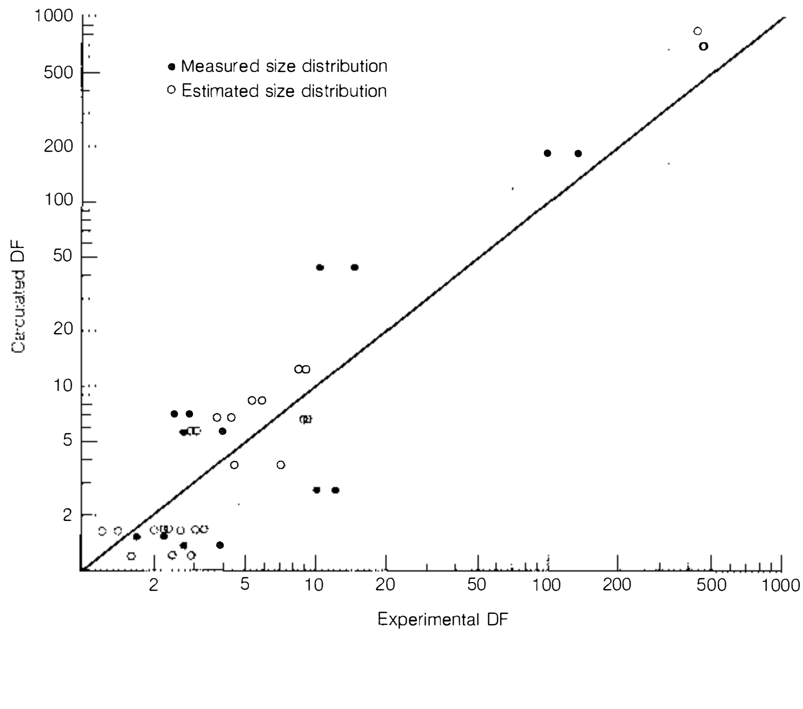


Figure 5 SUPRA was used to calculate DFs for some of the EPRI experiments. Estimated particle size distributions were used for those tests where measurements were not taken, and these estimates were based on measured distributions from other tests. A perfect correspondence between the experimental value and the SUPRA calculated value is represented by the black 45° line. Values above the line represent overprediction of DF by SUPRA. The gray lines represent a factor of 2 in DFs higher or lower than the 45° line. Values between the lines are considered a very good comparison.

New Contracts

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
Advanced Power Systems				
RP1193-6	Amorphous Silicon Alloys for Tandem Solar Cells	20 months	610.9	Princeton University *J. Crowley*
RP1654-20	Testing of Selexol Absorption Process for Simulation Model Verification	5 months	44.9	Tennessee Valley Authority *G. Quentin*
RP2048-6	Materials for IGCC Plants: Aqueous Corrosion in Gray Water Environments	1 year	100.0	IIT Research Institute *W. Bakker, B. Syrett*
RP2382-2	Combustion Turbine Material Problems	8 months	142.9	Battelle Memorial Institute *R. Viswanathan*
RP2467-1	High-Reliability Gas Turbine Controls and Accessories	30 months	2089.9	General Electric Co. *C. Dohner*
RP2501-1	Wellhead Binary-Cycle Power Plant Evaluation	13 months	266.9	Fluor Engineers, Inc. *S. Kohan*
Coal Combustion Systems				
RP717-3	AFBC Boiler Conversion Study	9 months	246.9	Northern States Power Co. *S. Drenker*
RP1403-8	Improved Low-Pressure Rotor Forging Demonstration	8 months	49.6	Vereinigte Edelstahlwerke Ag *R. Jaffee*
RP1681-2	Power Plant Performance Instrumentation System	37 months	1676.0	Potomac Electric Power Co. *F. Wong*
RP1839-4	Modification of Coal Ash Deposits by Using Volatile Additives	5 months	71.3	Battelle Memorial Institute *J. Dimmer*
RP1860-7	6 × 6 AFBC Test Program Data Evaluation	8 months	51.6	Foster Wheeler Boiler Corp. *W. Howe*
RP2113-4	Cooling-Tower Performance Test Facility: Data Analysis	16 months	263.1	Environmental Systems Corp. *J. Bartz*
RP2533-3	Joint Symposium on Dry SO_2 Control	9 months	30.8	Acurex Corp. *M. McElroy*
RP2535-1	Mist Elimination Field Studies	25 months	626.2	Stearns Catalytic Corp. *R. Rhudy*
Electrical Systems				
RP1999-6	Decision Theory Approach to Bad Data Identification in State Estimation	1 year	50.0	University of California at Berkeley *M. Pereira*
RP2153-2	Power Plant Performance Instrumentation System	37 months	1676.0	Potomac Electric Power Co. *J. Lamont*

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP2473-3	Hypergeometric Approximation Feasibility Study	8 months	50.0	Lawrence Berkeley Laboratory *M. Pereira*
Energy Analysis and Environment				
RP1216-9	Demonstration of Commercial Survey Techniques	16 months	168.5	Applied Management Sciences, Inc. *J. Wharton*
RP1537-2	Application of Consumer Research in Electric Utilities	15 months	120.0	University of Michigan *J. Wharton*
RP1585-12	Cost-Size Relationships: Impact on the Market Potential of Nuclear Power Technologies	4 months	40.2	Decision Focus, Inc. *S. Chapel*
RP1585-13	Costs and Benefits of Smaller Nuclear Plants	4 months	40.0	Applied Decision Analysis, Inc. *S. Chapel*
RP1630-25	Large Eddy Simulation of Plume Transport and Dispersion	34 months	562.0	Research Institute of Colorado *D. Lawson*
RP1630-28	Measurement of S (IV), HCHO, and the HCHO–S (IV) Adduct in the Atmosphere	2 years	89.7	Texas Tech University *D. Lawson*
RP1814-11	Transfer of Energy and Environmental Analysis Models to Utilities	1 year	40.0	Mindware Corp. *D. Fromholzer*
RP1817-2	Behavioral Effects of Air Ions	58 months	1500.0	Research Foundation for Mental Hygiene, Inc. *R. Kavet*
RP1819-4	Utility Planning Model: Maintenance and Support	13 months	201.2	Arthur Andersen & Co. *L. Rubin*
RP1946-5	Health Risks From Airborne Toxics	11 months	25.1	IWG Corp. *R. Wyzga*
RP2310-2	Comparison of Carcinogenic Potencies in Animals and Humans and Use in Quantitative Risk Assessment	11 months	44.9	Science Research Systems. Inc. *A. Silvers*
RP2342-1	Generalizing Utility Experiments	10 months	147.9	Minimax Research Corp. *J. Chamberlin*
RP2378-9	Feasibility of Studying Telephone Linemen to Determine Leukemia Risks From Electromagnetic Fields	4 months	55.3	Johns Hopkins University *C. Young*
RP2381-8	Value of Consumer Load Data	4 months	25.0	Economic Systems Research Associates *E. Beardsworth*

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP2440-1	Impact of Rate Structure on Energy Management Program	16 months	225.0	National Economic Research Associates, Inc. *J. Chamberlin*
RP2482-1	Analysis of EPA Assessment: Fossil Fuel Pollutant Impacts on Public Health	3 months	51.0	Systems Applications, Inc. *W. Weyzen*
RP2482-2	Characterization of Particulate Matter in Utility Work Areas: Phase 1	5 months	52.2	Radian Corp. *W. Weyzen*
RP2491-1	Visibility Data Integration	3 years	868.4	University of Utah Research Institute *P. Mueller*
RP2548-1	Demand-Side Management	35 months	775.0	Battelle, Columbus Laboratories *A. Faruqui*
RP2553-1	Risk Assessment in Aquatic Ecology: Population-Level Analysis	9 months	75.0	Applied Biomathematics, Inc. *A. Silvers*

Energy Management and Utilization

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP1041-17	TiC-Supported Catalyst Preparation	8 months	45.0	Prototech Co. *A. Appleby*
RP1086-18	Technical-Economic Evaluation of Large-Scale Electrolytic Hydrogen Production Technologies	4 months	59.3	Stone & Webster Engineering Corp. *B. Mehta*
RP1745-14	Topical Manuals on Hydroelectric Generation	19 months	149.0	International Engineering Co., Inc. *C. Sullivan*
RP1745-15	Small-Hydro Technology Transfer	13 months	159.3	International Engineering Co., Inc. *C. Sullivan*
RP1745-16	Small-Hydro Technology Transfer	13 months	158.0	International Engineering Co., Inc. *C. Sullivan*
RP1940-10	Review of Efficient Energy Use Technologies	17 months	140.0	Synergic Resources Corp. *S. Braithwait*
RP1940-12	Survey of Commercial-Sector Demand-Side Management Activities	10 months	69.0	Synergic Resources Corp. *V. Rabl*
RP2033-12	R&D Planning Workshop on Ground-Coupled Heat Pumps	6 months	44.8	Hart, McMurphy & Parks *G. Purcell*
RP2034-12	Seminar on Buildings and Their Energy Systems	10 months	52.5	Policy Research Association *O. Zimmerman*
RP2036-16	Heat Storage System Sizing Under Utility Rate Schedules	10 months	85.0	Electric Power Software Corp. *V. Rabl*
RP2285-7	Seminar on Energy-Efficient Lighting	5 months	44.7	Government Institutes, Inc. *S. Pertusiello*
RP2415-2	Fleet Electric Vehicle: Lithium–Metal Sulfide Battery Development and Submodule Demonstration	18 months	304.4	Argonne National Laboratory *R. Weaver*
RP2416-20	Electric Glassmaking Scoping Study	7 months	58.5	Ashfield Associates *L. Harry*
RP2418-1	Interaction of Energy-Efficient Lighting and HVAC Systems in Commercial Buildings	7 months	196.7	Dubin-Bloome Associates *G. Purcell*
RP2418-3	Retrofit Luminaire Performance	9 months	47.2	Lighting Technologies *S. Pertusiello*
RP2488-2	Analysis of Compressed-Air Energy Storage Plant in 25–50-MW Range	15 months	100.0	BBC Brown Boveri, Inc. *R. Schainker*
RP2488-3	CAES Two-Phase Flow Instability, Control, and Calibration Analysis	18 months	108.0	United Technologies Research Center *R. Schainker*
RP2488-4	Thermal Cycling Test on a Section of a CAES Recuperator	15 months	130.5	Encotech, Inc. *B. Mehta*
RP2597-2	Data and Methodology for End-Use Analysis	9 months	121.7	Decision Focus, Inc. *T. Yau*

Nuclear Power

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP495-5	MMS Code Analysis of FIST Data	9 months	35.3	S. Levy, Inc. *S. Kalra*
RP1557-15	Advanced Radwaste Compaction Techniques	10 months	83.7	Combustion Engineering, Inc. *M. Naughton*
RP1757-35	ASME Appendix on Service Environment	5 months	25.0	Westinghouse Electric Corp. *S. Tagart*
RP1930-10	Hydrogen Water Chemistry: Fuel Materials	44 months	1260.3	General Electric Co. *A. Machiels*
RP1936-5	QUANDRY/PDQ Depletion Test	8 months	29.6	Massachusetts Institute of Technology *W. Eich*
RP2058-12	Stress Corrosion Cracking of Alternative Bolting Alloys	6 months	30.0	Battelle, Columbus Laboratories *W. Childs*
RP2299-2	Critical Flow Through Small Breaks	11 months	300.0	EG&G Idaho, Inc. *G. Srikantiah*
RP2347-15	Application of Artificial Reasoning Systems to Operator Decision Aids	4 months	39.9	IntelliGenetics *D. Cain*

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP2356-21	Evaluation of Eastern U.S. Seismic Source Zones	15 months	199.4	Law Engineering Testing Co. *J. King*
RP2356-22	Evaluation of Eastern U.S. Seismic Source Zones	15 months	226.1	Woodward-Clyde Consultants *C. Stepp*
RP2356-23	Evaluation of Eastern U.S. Seismic Source Zones	15 months	218.5	Bechtel Group, Inc. *C. Stepp*
RP2394-10	Safety Assessment Task Order	8 months	30.0	Science Applications, Inc. *J. Gaertner*
RP2395-4	MMS Code Evaluation of Emergency Response Guidelines and Control Systems	9 months	50.0	Duke Power Co. *M. Divakaruni*
RP2395-5	Compact BWR Analyzer	7 months	96.3	S. Levy, Inc. *D. Cain*
RP2414-3	Assessment of Advanced Radwaste Drying Methods	15 months	196.8	IIT Research Institute *M. Naughton*
RP2420-13	BWR ATWS Support Analysis	4 months	25.0	Science Applications, Inc. *B. Chexal*
RP2430-23	Large-Scale Prototype Breeder Cost Estimate	7 months	241.5	Southern Electric International, Inc. *D. Gibbs*
RP2448-3	Digital Feedwater Control in a BWR	34 months	410.4	Science Applications, Inc. *M. Divakarunl*
RP2448-4	BWR Signal Validation Evaluation for Reliability and Protection Against Common Cause Failures	7 months	32.1	Los Alamos Technical Associates, Inc. *B. Sun*
RP2453-4	MMS Simulation and Analysis of Semiscale Steam Generator Tube Rupture Tests	11 months	59.9	Science Applications, Inc. *S. Kalra*
RP2455-2	Variability of Fracture Toughness of Nuclear Pressure Vessel Steel	10 months	45.0	Materials Research and Computer Simulation *R. Nickell*
RP2457-2	Flaw Evaluation Procedure for Ferritic Piping	13 months	106.5	General Electric Co. *D. Norris*
RP2514-2	Nuclear Plant Constructibility Assessment Study	7 months	50.0	Lavin Associates *J. Carey*
RP2515-2	Some Nonlinear Mechanical Systems and Their Application to Nuclear Power Plants	34 months	72.8	Wayne State University *F. Gelhaus*
RP2515-4	Charged-Droplet Transport and Corrosion in Wet Steam Flows	7 months	50.0	General Electric Co. *N. Hirota*
RP2519-1	Maintenance Equipment Applications Center	1 year	520.9	J. A. Jones Applied Research Co. *M. Kolar*
R&D Staff				
RP2426-5	Design of an Improved Cr-Mo-V Steel Structure-Property Relationship	22 months	45.2	Technische Universitat Hamburg-Harburg *R. Jaffee*

New Technical Reports

Each issue of the *Journal* includes information on EPRI's recently published reports.

Inquiries on technical content may be directed to the EPRI project manager named at the end of each entry: P.O. Box 10412, Palo Alto, California 94303; (415) 855-2000.

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ADVANCED POWER SYSTEMS

10-MW (e) Solar-Thermal Central-Receiver Pilot Plant
AP-3285 Final Report (RP2003-2); Vol. 1, $17.50; Vol. 2, $44.50
Contractor: Burns & McDonnell Engineering Co.
EPRI Project Manager: J. Bigger

Evaluation of Exxon Donor Solvent Full-Range Distillate as a Utility Boiler Fuel
AP-3360 Final Report (RP2112-4); $22.00
Contractor: Energy and Environmental Research Corp.
EPRI Project Manager: H. Schreiber

Transient Electrical Behavior in Magnetohydrodynamic Generators
AP-3399 Final Report (RP468-3); $23.50
Contractor: Stanford University
EPRI Project Managers: A. Dolbec, P. Zygielbaum, A. Lowenstein

Development of an EPRI Reliability Assessment System for Combined-Cycle Power Plants
AP-3420 Interim Report (RP990-7); $11.50
Contractor: Arinc Research Corp.
EPRI Project Manager: R. Duncan

Transportation and Handling of Medium-Btu Gas in Pipelines
AP-3426 Final Report (RP2111-1); $14.50
Contractor: Air Products and Chemicals, Inc.
EPRI Project Manager: G. Quentin

Inertial Confinement Fusion: Technical Forecast Handbook
AP-3429 Topical Report (RP1972-1); $17.50
Contractors: TRW Energy Development Group; Woodward-Clyde Consultants
EPRI Project Manager: K. Billman

Pilot Plant Evaluation of Exxon Donor Solvent Residue for the Texaco Coal Gasification Process
AP-3440 Final Report (RP714-4); $10.00
Contractor: Texaco, Inc.
EPRI Project Manager: W. Weber

Wind Turbine Performance Assessment: Technology Status Report No. 7
AP-3447 Final Report (RP1996-1); $14.50
Contractor: Arthur D. Little, Inc.
EPRI Project Manager: F. Goodman

Cost and Performance for Commercial Applications of Texaco-Based Gasification–Combined-Cycle Plants
AP-3486 Final Report (RP2029-10); Vol. 1, $13.00; Vol. 2, $28.00
Contractor: Fluor Engineers, Inc.
EPRI Project Managers: M. Gluckman, A. Lewis

Low-Purity Oxygen Production Study
AP-3499 Final Report (RP2221-2); $10.00
Contractor: Cryogenic Consulting Service, Inc.
EPRI Project Manager: T. O'Shea

COAL COMBUSTION SYSTEMS

Coal Combustion By-Products Utilization Manual: Evaluating the Utilization Option
CS-3122 Final Report (RP1850-1), Vol. 1; $47.50
Contractor: Michael Baker, Jr., Inc.
EPRI Project Manager: R. Komai

Utility FGD Survey, July 1982–March 1983
CS-3369 Topical Report (RP982-32); Vol. 1, $29.50; Vol. 2, $71.50
Contractor: Pedco Environmental, Inc.
EPRI Project Manager: C. Dene

Erosion-Corrosion by High-Velocity Particles in Fluidized-Bed Combustion Systems
CS-3396 Final Report (RP979-4); $14.50
Contractor: United Technologies Corp.
EPRI Project Manager: J. Stringer

User's Manual: Cooling-Tower-Plume Prediction Code
CS-3403-CCM Computer Code Manual (RP906-1); $20.50
Contractor: Argonne National Laboratory
EPRI Project Manager: J. Bartz

Coal-Water-Slurry Evaluation
CS-3413 Final Report (RP1895-3); Vol. 1, $23.50; Vol. 2, $20.50
Contractor: Babcock & Wilcox Co.
EPRI Project Manager: R. Manfred

Method for Predicting the Effective Volume Resistivity of Sodium-Depleted Fly Ash Layers in Hot-Side Electrostatic Precipitators
CS-3421 Final Report (RP724-2); $10.00
Contractor: Southern Research Institute
EPRI Project Manager: R. Altman

Hot-Gas Filtration for Pressurized Fluidized-Bed Combustion
CS-3427 Topical Report (RP1336-4); $14.50
Contractor: Acurex Corp.
EPRI Project Manager: S. Drenker

Acoustic Emissions From Crack Growth in Steam Turbine Rotor Steels
CS-3428 Final Report (RP734-3); $28.00
Contractor: Science Applications, Inc.
EPRI Project Manager: A. Armor

Stabilization of Power Plant By-Product Storage Sites for Building Development
CS-3475 Final Report (RP1685-6); $17.50
Contractor: Michael Baker, Jr., Inc.
EPRI Project Manager: D. Golden

Evaluation of an Advanced Dual-Register Coal Burner for Utility Boiler NO_x Control
CS-3503 Final Report (RP899-1); $10.00
Contractor: Babcock & Wilcox Co.
EPRI Project Manager: M. McElroy

ELECTRICAL SYSTEMS

Considerations in Designing and Using Power System Operator Training Simulators
EL-3192 Final Report (RP1915-1); $23.50
Contractor: Electrocon International, Inc.
EPRI Project Manager: C. Frank

Fault Protection for High-Phase-Order Transmission Lines
EL-3316 Final Report (RP1764-5); Vol. 1, $17.50; Vol. 2 (Computer Code Manual), $20.50
Contractor: Auburn University
EPRI Project Manager: J. Lamont

Maximum Safe Pulling Lengths for Solid-Dielectric-Insulated Cables
EL-3333 Final Report (RP1519-1); Vol. 1, $17.50; Vol. 2 (Computer Code Manual), $11.50
Contractors: Pirelli Cable Corp.; Georgia Power Co.
EPRI Project Manager: T. Kendrew

PCB Removal From Transformers
EL-3345 Final Report (RP2028-2); $13.00
Contractor: Franklin Research Center
EPRI Project Manager: G. Addis

Stator Coil Wedge Tightness Detector
EL-3358 Final Report (RP2308-3); $8.50
Contractor: VinTek, Inc.
EPRI Project Manager: D. Sharma

Improvement in Accuracy of Prediction of Electrical Machine Constants (Vol. 1); **Generator Models for Subsynchronous Resonance Conditions** (Vol. 2)
EL-3359 Final Report (RP1288-1, RP1513-1); Vol. 1, $23.50; Vol. 2, $26.50
Contractor: General Electric Co.
EPRI Project Manager: D. Sharma

Electrochemical Machining Development for Turbine Generator Rotor Slots
EL-3390 Final Report (RP1823-1); $23.50
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: J. Edmonds

High-Voltage Stator Winding Development
EL-3391 Final Report (RP1716-1); $23.50
Contractor: General Electric Co.
EPRI Project Manager: J. Edmonds

Workshop Proceedings: Electrical Testing of Extruded-Dielectric Power Transmission Cables
EL-3415 Proceedings (WS80-169); $11.50
Contractor: Cable Technology Laboratories, Inc.
EPRI Project Manager: F. Garcia

An Approach for Determining Transfer Capability Objectives
EL-3425 Final Report (RP1960-1); Vol. 1, $13.00, Vol. 2 (Computer Code Manual), $16.00
Contractor: Power Technologies, Inc.
EPRI Project Manager: J. Mitsche

Utility Survey of Methods for Minimizing the Number and Severity of System Separations
EL-3437 Final Report (RP1952-1); $14.50
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EPRI Project Manager: J. Mitsche

ENERGY ANALYSIS AND ENVIRONMENT

Regional Load-Curve Models: Data Base
EA-1672 Final Report (RP1008), Vol. 5; $10.00
Contractor: Harlan D. Platt
EPRI Project Manager: A. Faruqui

Plume Model Validation and Development; Field Measurements: Plains Site
EA-3064 Final Report (RP1616-8); $19.00
Contractor: Rockwell International Corp.
EPRI Project Manager: G. Hilst

Evaluation of Three First-Order Closure Models: Plains Site
EA-3078 Final Report (RP1616-9); $43.00
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EPRI Project Manager: G. Hilst

Chemical Attenuation Rates, Coefficients, and Constants in Leachate Migration
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EPRI Project Manager: V. Niemeyer

Proceedings: EPRI Load Research Symposium
EA-3389 Proceedings (RP2279-3); $32.50
Contractor: Battelle Memorial Institute
EPRI Project Manager: E. Beardsworth

Geohydrochemical Models for Solute Migration: Process Description and Computer Code Selection
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EPRI Project Manager: I. Murarka

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EA-3442 Final Report (RP1366-1), Vol. 1; $17.50
Contractor: Resources for the Future, Inc.
EPRI Project Manager: S. Braithwait

Nonutility Demand for Coal
EA-3456 Final Report (RP1213); Vol. 1, $19.00; Vol. 2, $17.50
Contractor: ICF Incorporated
EPRI Project Manager: S. Braithwait

Industrial Energy Substitution: Econometric Analysis of U.S. Data, 1958–1974
EA-3462 Final Report (RP1475-1); $34.00
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EPRI Project Manager: A. Faruqui

Workshop Proceedings: Planning and Assessment of Load Management
EA-3464 Proceedings (RP1050-2); $26.50
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Atmospheric Retention of Anthropogenic CO_2: Scenario Dependence of the Airborne Fraction
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EPRI Project Manager: E. Beardsworth

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EPRI Project Managers: A. Halter, V. Niemeyer

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Contractor: Tennessee Valley Authority
EPRI Project Manager: R. Goldstein

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EPRI Project Manager: D. Geraghty

ENERGY MANAGEMENT AND UTILIZATION

BEST Facility: Third Progress Report
EM-2995 Interim Report (RP255-2); $13.00
Contractor: Public Service Electric and Gas Co.
EPRI Project Manager: W. Spindler

Cogeneration Systems Design for Enhanced Oil Recovery
EM-3424 Final Report (RP1276-9); Vol. 1, $10.00; Vol. 2, $13.00; Vol. 3, $25.00; Vol. 4, $23.50
Contractor: RMR Associates
EPRI Project Managers: D. Hu, R. Mauro

Hydropower Reliability Study
EM-3435 Final Report (RP1745-5); $43.00
Contractors: Motor Columbus Consulting Engineers, Inc.; Black & Veatch Engineers-Architects
EPRI Project Manager: C. Sullivan

Conceptual Design and Cost of a Superconducting Magnetic Energy Storage Plant
EM-3457 Final Report (RP1199-17); $46.00
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EPRI Project Manager: R. Schainker

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EM-3469 Final Report (RP2034-3); $13.00
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EPRI Project Manager: A. Lannus

NUCLEAR POWER

Core Design and Operating Data for Cycles 2 and 3 of Hatch-1
NP-2106 Final Report (RP130-4); $14.50
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EPRI Project Manager: O. Ozer

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EPRI Project Manager: M. Merilo

Secondary Water Chemistry at Oconee
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EPRI Project Manager: C. Welty

Determination and Verification of Required Water Chemistry Limits: Summary Report
NP-3274 Final Report (RPS111-1), Vol. 1; $23.50
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Contractors: Acurex Corp.; CHAM of North America, Inc.
EPRI Project Manager: S. Kalra

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PWR Radiation Fields Through 1982
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EPRI Project Manager: R. Shaw

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EPRI Project Manager: A. Adamantiades

Neutron Multiplicities of Cf-252 and the Fissile Nuclei
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EPRI Project Manager: O. Ozer

Historical Method of Seismic Hazard Analysis
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EPRI Project Manager: D. Worledge

High-Temperature Electromagnetic Filtration on the Primary Circuit of the Winfrith 100-MW Nuclear Plant
NP-3441 Interim Report (RP1445-4); $11.50
Contractor: United Kingdom Atomic Energy Authority
EPRI Project Manager: C. Wood

Procedure for Reviewing and Improving Power Plant Alarm Systems
NP-3448 Interim Report (RP2011-2); Vol. 1, $23.50; Vol. 2, $14.50
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EPRI Project Manager: J. O'Brien

Experimental Study of the Diversion Cross-Flow Caused by Subchannel Blockages: Single-Phase Flow
NP-3459 Interim Report (RP1378-1), Vol. 1; $17.50
Contractor: Ecole Polytechnique, Université de Montreal
EPRI Project Manager: M. Merilo

Corrosion-Product Release in LWRs
NP-3460 Interim Report (RP2008-1); $14.50
Contractor: Atomic Energy of Canada, Ltd.
EPRI Project Manager: H. Ocken

Effects of Shutdown/Cooldown Techniques on Radiation Fields in PWR Primary Coolant Loops
NP-3461 Interim Report (RP825-1); $11.50
Contractor: Babcock & Wilcox Co.
EPRI Project Manager: R. Shaw

Coolant Chemistry Effects on Radioactivity at Two PWR Plants
NP-3463 Interim Report (RP825-2); $19.00
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: R. Shaw

Decay Heat Removal Experiments in a U-Tube Steam Generator One-Loop Test Facility
NP-3472 Final Report (RP1731-1); $14.50
Contractor: SRI International
EPRI Project Manager: J. Sursock

PWR Waste Gas System Analysis
NP-3476 Final Report (RP1560-1); $11.50
Contractor: Impell Corp.
EPRI Project Manager: M. Naughton

PWR Steam Generator Chemical-Cleaning Data Base
NP-3477 Final Report (RPS305-2); Vol. 1, $10.00; Vol. 2, $19.00
Contractor: Aptech Engineering Services, Inc.
EPRI Project Manager: C. Williams

Fractographic Evaluation of Specimens of A533B Pressure Vessel Steel
NP-3483 Final Report (RP1325-7); $17.50
Contractor: Technical Research Center of Finland
EPRI Project Manager: R. Jones

PLANNING AND EVALUATION

1984–1988 Research and Development Program Plan
P-3404-SR Special Report; $10.00
EPRI Project Manager: J. Arcella

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