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Robots for Nuclear Plants

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Cover: Advanced robots may not evolve to look like humans, but they are being designed with capabilities far beyond those of the single-function robotic devices currently used in nuclear plant inspection and maintenance. Functional versatility, greater mobility, and sophisticated control and feedback systems are at the center of ongoing research.

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The Robotics Evolution

Robotics technology holds promise for contributing to a threefold need in nuclear power plant maintenance: the need to improve preventive maintenance through in-service inspection and on-line surveillance, the need to reduce the cost of maintenance, and the need to reduce occupational radiation exposure incurred in carrying out inspection and maintenance. Elements of robotics technology are already contributing to these concerns in the field, but the applications generally are limited to single-purpose devices that are preprogrammed and provide no feedback to their human controllers. Still, limited as it is, the technology applied to date amounts to an unheralded automation revolution.

A large part of the inspection and repair of steam generators is now performed with automated, preprogrammed robotic devices. Such devices walk along the bottom surface of steam generator tubesheets, for example, cleaning the inner surfaces of the tube ends and inserting plugs to maintain steam generator tube integrity. Other automated probes, armed with computerized diagnostic aids, search the tubes for signs of deterioration. Similarly, ultrasonic detectors, mounted on remotely operated scanners, traverse primary coolant piping, sending signals to portable computers that can characterize defects. Automatic devices have been developed that cut pipe, weld pipe, grind weld contours, and perform operations needed to repair nuclear plant primary piping. Automatic, remotely controlled devices have also been developed for such diverse tasks as processing ion-exchange resins and changing pins in control rod guide tubes. These devices have been developed by reactor manufacturers, nuclear service companies, and EPRI.

This success with single-function robotic devices gives us confidence that the evolution to true robots with artificial intelligence, multipurpose functions, and in situ feedback is in the nuclear industry's future. Some early prototypes of such robots, nicknamed Rover and IRIS, are under initial testing by EPRI at TMI-2 and EPRI's NDE Center, respectively. However, full realization of advanced functions is still a long way off. The simple matter of visualizing an array of pipes and then maneuvering through them to reach a specific location and perform a specific function is elementary for humans but requires a major development in robotics.

On the other hand, robots already have some capabilities that humans will never develop—for example, the ability to enter a high-temperature, radiation environment without cumbersome anticontamination clothing and other protection. We can foresee the day when today's single-purpose automatons will be replaced with a modest number of sophisticated, multifunctional robot workers that can handle a variety of tasks in such environments. The nicest thing about that prospect is that no one will resent their appearance because the jobs they will be doing are not sought after by humans.

John Taylor, Vice President
Nuclear Power Division

Authors and Articles

Robots are still envisioned mostly as lockstepped laborers that do repetitive tasks on manufacturing assembly lines. But in fact, the higher functions of true robots (programmable versatility, mobility, and artificial intelligence) are commending them for intricate, one-of-a-kind jobs in places where humans cannot even go. This month's cover story, **Robots Join the Nuclear Workforce** (page 6), focuses on R&D, much of it sponsored by EPRI, whose eventual products should expedite a number of inspection, service, and repair routines in radioactive or thermally hot areas of power plants, perhaps even while they operate. To prepare his article, the *Journal*'s Taylor Moore visited robotics researchers at Carnegie-Mellon University, observed applications research at Three Mile Island and at EPRI's NDE Center, and drew from related work under three Nuclear Power Division research managers.

Floyd Gelhaus, a program manager for plant availability R&D, came to EPRI in April 1974 after six years with General Electric Co. and two earlier years with RCA. At EPRI he worked for some time in fault analysis and modeling reactor and steam cycle systems, then (after a year and a half on loan to Northeast Utilities in 1981-1982) turned to developments for plant maintenance and repair, including a focus on robotics.

Adrian Roberts, senior program manager for reactor fuels and materials, has been with EPRI since September 1974, managing research projects in core materials until 1979, spending a year at Cornell University as a visiting professor in materials science, and then returning to EPRI to head a research program. Roberts was formerly with Argonne National Laboratory for six years.

Michael Kolar came to EPRI in February 1978 as a technical specialist in nuclear systems and materials. He later worked for a year in the Nuclear Safety Analysis Center, then became senior program manager for availability before leaving EPRI last summer to join Science Applications, Inc. Kolar had earlier worked in safety analysis for five years with Gilbert/Commonwealth, taught mathematics for four years at Cleveland State University, and worked as a nuclear engineer for seven years at NASA's Lewis Research Center.

■

Putting up the storm windows and remembering where the candle stubs are kept—that's about the extent of storm preparation for most of us. **Utilities Weather the Storm** (page 18) describes how utilities must plan to repair storm damage. Nadine Lihach, the *Journal*'s senior feature writer, interviewed utilities who have come to grips with hurricanes, ice storms, and even volcanic ash. She also drew information from three Electrical Systems Division research managers whose programs have investigated weather phenomena and weather-resistant equipment designs.

Robert Iveson, manager of the Power System Planning and Operations Program, came to EPRI in April 1979. He was formerly with New York State Electric & Gas Corp. for 20 years, including 9 years as supervisor of transmission planning for the New York Power Pool.

Richard Kennon, manager of the Overhead Transmission Lines Program since 1978, has been with EPRI since February 1975. Formerly with Westinghouse Electric Corp. for nearly 23 years, he worked in marketing, moved into engineering, and was named manager of capacitor equipment engineering in 1970.

William Shula, manager of the Distribution Program, became an EPRI staff member in June 1976, after a year on loan from Texas Electric Service Co. He was with the utility for 27 years, including 8 years in charge of distribution planning.

■

Burner and furnace designs for low-NO_x combustion in a few new coal-fired power plants are one thing. Retrofit burners and furnace modifications for the same purpose in all sorts of older plants are something else. **The Retrofit Challenge in NO_x Control** (page 26) reviews the major R&D moves to adapt new technology for use where the need may be greatest. Taylor Moore wrote the article, with technical guidance from staff members of EPRI's Air Quality Control Program.

David Eskinazi, a project manager who came to EPRI in July 1982, has specialized in the fluid mechanics of power plant combustion and exhaust systems. He was formerly a senior staff engineer with Dynatech R/D Co. for three years.

Michael McElroy joined EPRI in October 1976, and his work has increasingly focused on NO_X control. He is now responsible for that area of the program. McElroy was formerly a field research engineer for KVB, Inc., consulting with utilities on emission measurements and controls.

Robert Carr, manager of the Air Quality Control Program since April 1982, has been at EPRI since March 1974. Much of his R&D management work at the Institute has been devoted to baghouses and fabric filters. Like McElroy, Carr was formerly a test engineer and utility consultant with KVB, Inc.

■

Refinement and ever-wider use of an EPRI computer code first released in 1978 have recently culminated in its formal approval for use in nuclear power plant licensing applications. **RETRAN: Code for Transients** (page 34) traces this important EPRI software development. Science writer John Douglas was aided by Lance Agee of the Safety Technology Department in EPRI's Nuclear Power Division.

Agee has been with the Institute since 1975, first as a project engineer, later as manager of thermohydraulic analysis projects, and since 1980 as a program manager for system and component code development. Agee was formerly with Combustion Engineering, Inc., for four years, working in safety and licensing. Still earlier, he worked for Douglas United Nuclear, Inc.


Kennon

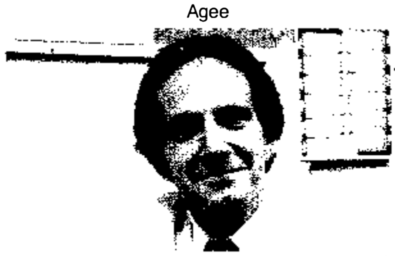

Shula


Roberts


Gelhaus


Agee


Iveson


Eskinazi

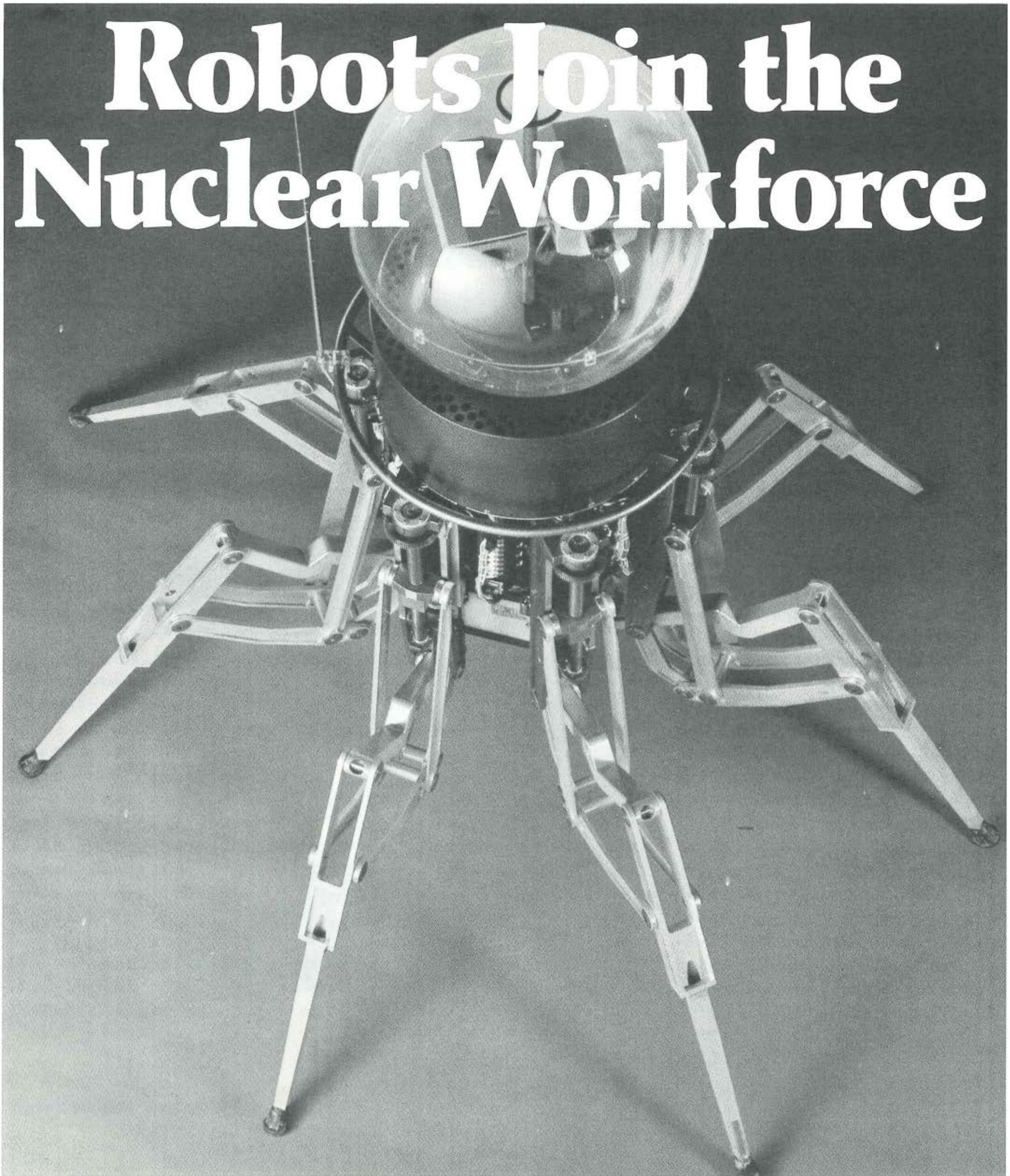

Carr


McElroy


Kolar

Robotics technology is already used in nuclear plants for such specialized tasks as remote welding and pipe inspection. Advanced robots now being developed will have greater mobility and be able to handle a variety of functions with the aid of on-board microprocessors. Their application should reduce both plant outages and personnel radiation exposure.

Robots Join the Nuclear Workforce



Once confined to the pages of science fiction, robots have dramatically captured the attention of the public and the industrial business community in recent years. Many observers view robots as a hallmark of neoindustrialization, breathing renewed economic vigor and competitiveness into depressed industries through improved productivity and reduced labor costs.

At the same time, however, workers often respond with apprehension to the mental image of a robot performing a task that formerly required a human. The social implications of the robotization of American industry will surely become of more concern to workers, managers, and policymakers alike as more robots enter the industrial workplace.

According to the Robotics Industries Association, only 6300 robots had been delivered in the United States by the end of 1983; most of those had been installed since 1976. But the force of technologic change and the pressure of international economic competition promise an accelerated pace of robot deployment in the years ahead. Some experts predict that as many as 100,000 robots may be at work in this country by 1990—one-tenth of the total number projected worldwide.

For most industries in which robots have been or are expected to be applied in significant numbers, such as automobile production, metalworking, and machinery manufacture, the incentives to robotize relate directly to preserving or recapturing competitive advantage through lowered unit costs of production and improved product quality. But for some industries, the attraction of robots is their potential to work in hazardous environments, thereby reducing the human risks associated with the work.

The electric utility industry is one such industry. Although utilities are not viewed by most industrial robot manufacturers as a significant potential market, special-application robots are under development for performing inspection and maintenance tasks inside nuclear power plants, where radiation levels, heat, and humidity either rule out the presence of human workers or severely limit their ability to work. For many of these tasks in a nuclear plant, robots would be a welcome addition to the workforce, freeing humans from some of the more onerous and discomforting jobs and, possibly, permitting certain tasks to be performed while a plant remains on-line, thus avoiding costly plant downtime for inspection or maintenance.

Worldwide interest in robotics for nuclear applications is growing, evidenced by the attendance at a four-day topical meeting of the American Nuclear Society last April in Gatlinburg, Tennessee. Over 300 professionals, including 67 attendees representing 12 countries outside the United States, gathered to hear more than 50 presentations related to robotics and remote handling in hostile environments.

Some of the robots under development for utility applications represent the state of the art of robotics engineering, and the related research efforts could pioneer advances that have broad application to other industries. EPRI has several current projects aimed at evaluating the technical and economic potential for robot applications in utility operations and at translating the understanding gained from these efforts to the utility professionals who have work aplenty waiting for robots that prove reliable and cost-effective.

Such research is necessarily long range. The robotics industry, fewer than 20 years old by the broadest definition, remains in its infancy, awaiting substantial technical advances in vision systems, miniaturization, and computer controls before truly economic, versatile, and powerful robots are commonplace items of commerce. But R&D success with robots in recent years suggests that such machines will emerge from the laboratories and enter the commercial market before this decade is over. EPRI's research in robotic applications, at least in part, is intended to ensure that when that day arrives, utilities will have a clear understanding of the work robots can do for them and whether it makes economic sense to put them to work.

Robots for nuclear plants

The use of remotely operated and robotlike equipment to protect nuclear workers in high-radiation areas is not new. John Taylor, an EPRI vice president and director of the Nuclear Power Division, divides robotic equipment in nuclear applications into two broad categories: single-purpose devices with limited ability to perform different operations, and reprogrammable, multipurpose robots with some degree of computer-based artificial intelligence.

"I think the first category has reached a reasonable level of maturity," says Taylor. At EPRI's Nondestructive Evaluation (NDE) Center and among reactor manufacturers, nuclear service contractors, and some utilities, these types of devices are in use today for such tasks as pipe cutting, welding, steam generator tube inspection and repair, and ultrasonic scanning of pipe sections for crack detection. "These devices have proved to be absolutely essential; we simply could not get some jobs done without them," adds Taylor.

Robots in the second category, those with sufficient computer-based intelligence to support a variety of applications, "have a long way to go," in Taylor's words, before they can demonstrate significant practical benefit in nuclear plant operations. But, as Taylor adds, such robots are under development, and their initial trials are expected to provide valuable insight to their ultimate potential.

Soon after remote manipulator arms were developed for use in hot cells and fuel reprocessing activities, an arm mounted on a transporter with cameras and lights made its debut in the 1950s

1 Robotics technology for nuclear plant applications has been evolving since the earliest days of nuclear science, when remote manipulators were developed for use in shielded hot cells.

WHAT IS A ROBOT?

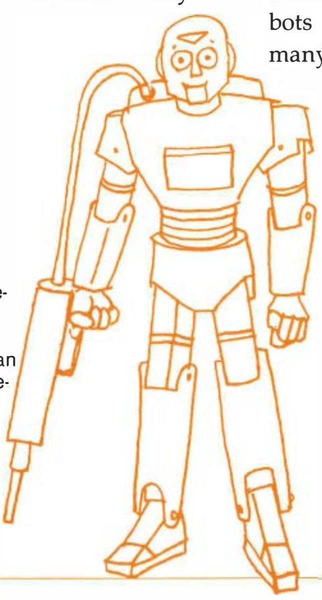
Robotic equipment represents a convergence of several technologies, some of which have been evolving for decades. According to a recent report to Congress by the Office of Technology Assessment, today's industrial robots have a dual technologic ancestry: industrial engineering automation, the roots of which can be traced back more than a century, and computer science and artificial intelligence, disciplines that are only a few decades old. Robot systems applicable in a nuclear plant will depend more on developments in this latter field; the basic component hardware adapted from industrial automation is considered sufficiently advanced for the prototype systems now under study.

Depending on how one defines a robot, today's devices can be seen as evolutionary descendants of tools developed in the earliest days of the nuclear industry. The word *robot* itself, first coined in the early 1920s by dramatist Karel Capek from the Czech word *robota*, or forced labor, connotes the functional basis of today's accepted definition. According to the Robotic Industries Association, a robot is a "reprogrammable multifunctional manipulator designed to move materials, parts, tools, or specialized devices, through variable programmed motions for the performance of a variety of tasks."

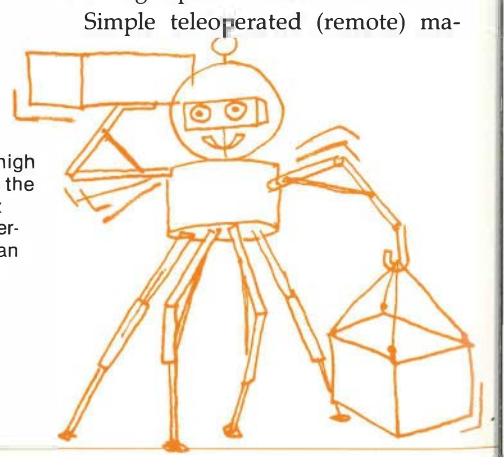
Few machines available or under development today truly qualify as robots under this strict definition. To many nuclear engineers, robots are simply improved, sophisticated versions of the remotely operated manipulator arms developed in the 1940s for handling radioactive materials viewed through lead-shielded windows from behind concrete walls. Place this artificial arm on a transport system, add television cameras or sensors for viewing, plus on-board computers for control and communication, and one has the basic elements of today's state-of-the-art robot.

A perhaps more useful approach to defining robots is the classification scheme used by the Japanese robotics industry. According to Dwight Sangrey, chairman of Carnegie-Mellon University's Department of Civil Engineering, which, along with CMU's Robotics Institute, is a leading U.S. center for robotics research, the Japanese classify robots in order of increasing sophistication.

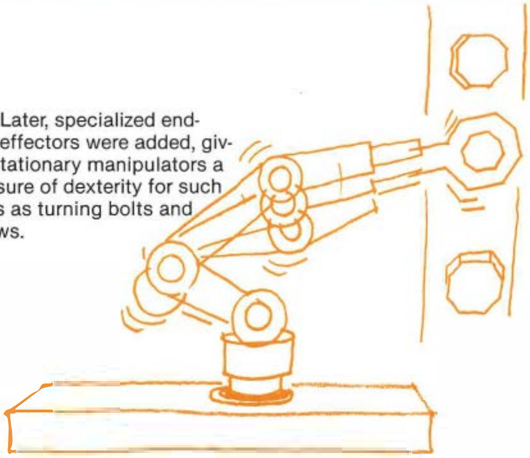
Simple teleoperated (remote) ma-



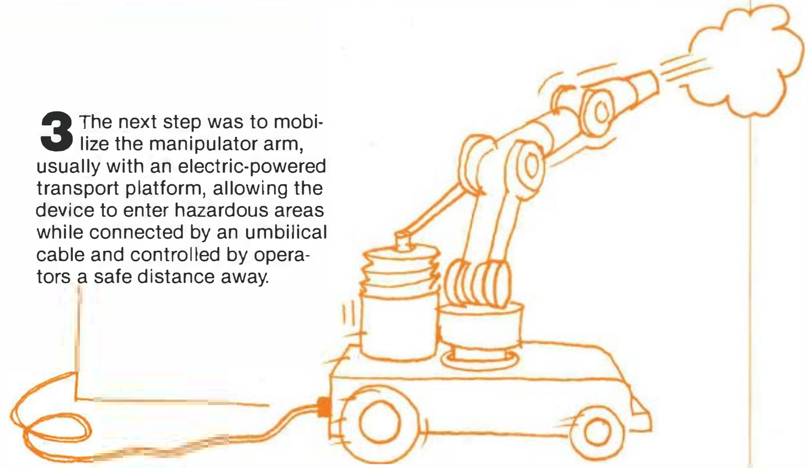
7 The ultimate robot may resemble the humanoid of science fiction—possessing greater agility and strength than humans while, like humans, being capable of logical reasoning.



6 Walking robots with a high degree of strength and the ability to negotiate complex obstacles are emerging; interchangeable manipulators can be added for special tasks.



2 Later, specialized end-effectors were added, giving stationary manipulators a measure of dexterity for such tasks as turning bolts and screws.



3 The next step was to mobilize the manipulator arm, usually with an electric-powered transport platform, allowing the device to enter hazardous areas while connected by an umbilical cable and controlled by operators a safe distance away.

nipulators are classed M1. Devices that can be programmed to perform a fixed sequence of repetitions are classed M2A; those capable of handling a variable sequence of programmed repetitions, M2B. More-sophisticated devices that can be taught a sequence of steps by an operator leading them through the motions are known as M3A; robots that are numerically controlled with a computer for a variety of tasks, M3B. The final classification, M4, is reserved for robots containing local, or artificial, intelligence that are capable of fully autonomous operation with self-contained reasoning.

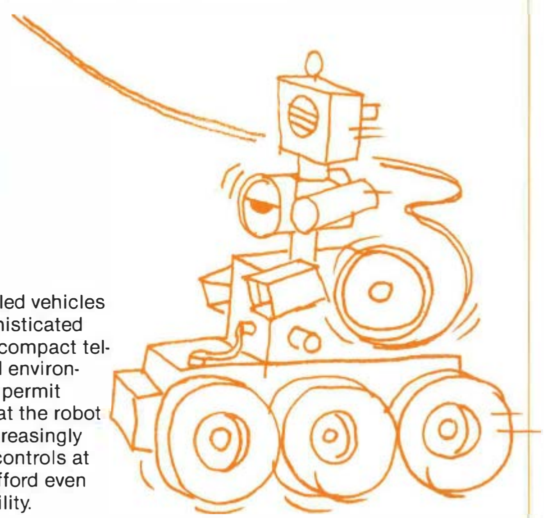
"The Japanese talk about their present R&D in construction robotics as being in the M3 level in the early 1990s," says Sangrey, who surveyed the Japanese robotics industry on a visit earlier this year, "and an M4 class of robots coming after the turn of the century. In the United States, we have sort of skipped over all these lower stages; we're now building robots at the M3 level, and in our laboratory right now we're constructing an M4 robot system. It is our better use and integration of computers and sensing technology that will enable us to make that jump."

As Sangrey is quick to point out, however, Japanese robotics technology for construction or utility plant applications, although perhaps not as technically sophisticated as some American projects, is more widely in use because the Japanese began developing their systems several years before the United States. The Japanese have also been under stronger economic pressure to develop robots because of a declining population of skilled workers.

"My sense is that the Japanese construction and nuclear power industries have a lead of several years," comments Sangrey. "They have very large and sophisticated pieces of unmanned equipment, although the machines are not robots in the sense of the vehicles we have built. They tend to be static pieces of construction equipment specifically designed for some task in, say, a nuclear reactor, such as cutting concrete.

"With few exceptions, the Japanese have not developed profitable applications of robotics," adds Sangrey. "They've just started within the last year to develop economically attractive robots for construction." □

5 State-of-the-art robots today are designed with some on-board electronic intelligence for more-complex operations and simple obstacle avoidance; radio signals can link robot and operator to enable increased range while maintaining data and video transmission.



4 Remote-controlled vehicles grew more sophisticated with the addition of compact television cameras and environmental sensors that permit operators to see what the robot sees as it works. Increasingly powerful computer controls at the operator's end afford even greater maneuverability.

at the government's Hanford nuclear facility in Washington State. Developed by Westinghouse Hanford Co., the remotely controlled transporter vehicle was dubbed Louie after a technician scrawled the nickname on the robot's arm. Louie has proved to be a versatile and long-lived workhorse and is still in use today.

Some fundamental aspects of how this equipment is applied distinguish robotic equipment for nuclear plant applications from the more widely familiar industrial robots—those fixed devices that typically are employed for pick-and-place operations or other highly repetitive tasks.

In many industrial applications of robots, the objective is to replace human workers with machines that are more productive, efficient, and accurate. But for nuclear applications, the objective is not so much to replace workers as it is to extend their presence—for example, to project their reach into areas of a nuclear plant where the thermal or radiation environment prohibits or limits a human presence.

"In contrast to most robotic applications, we want to keep man in the loop, rather than replace him, to observe the work, make decisions, and control the robot," according to R. K. Winkleblack, an EPRI project manager in the Nuclear Power Division. "Strictly speaking, the devices we are looking at are remote-controlled equipment, not true robots," adds Winkleblack.

Improving availability

The economic motivation to use robots for nuclear plant inspection and maintenance is centered on their potential for improving plant availability; a byproduct is the potential for reducing the occupational radiation exposure (ORE) of plant personnel.

Many inspection and maintenance tasks can only be done when the reactor is shut down because radiation levels under operating conditions would be too high even for humans fully outfitted in protective clothing. These jobs are usually deferred until scheduled refueling outages to minimize plant downtime. They thus can become part of the critical path of activity needed to bring the plant back into service.

Delays are critical to plant availability, as well as costly. Purchased replacement power to substitute for the output of a 1000-MW (e) reactor costs an average of $500,000 a day. Robots potentially could contribute to improved plant availability by avoiding delays in scheduled outages and handling some tasks while the reactor is operating.

Nuclear workers are currently limited by federal regulation to no more than 3 rem per quarter-year or an annual total of 5 rem. This means that for many routine jobs large numbers of workers must be assigned a small portion of the work because each will quickly reach the ORE limit and must then be restricted to nonradiation areas until the next quarter. Consequently, utilities are forced to employ significant numbers of transient workers, or so-called jumpers—temporary personnel who move on to other jobs after receiving the ORE limit.

According to a Nuclear Regulatory Commission (NRC) estimate, every man-rem of personnel exposure has a value to utilities of $1000, although some utilities assign a value of as much as $5000 a man-rem. Some types of work, such as health physics surveys and inspection of primary reactor cooling systems, can involve radiation fields of several hundred rads an hour.

Utilities may face even tougher ORE limits in the future. In addition to guidelines that call on utilities to reduce OREs to levels "as low as reasonably achievable," NRC for several years has been studying proposals to reduce the ORE standards; such a development could have a multiplicative effect on utility costs for personnel exposure.

Feasibility studied

EPRI and NRC have both sponsored preliminary assessments of the potential for applying robotics in nuclear power plants. NRC, motivated primarily by the objective of reducing personnel radiation doses, looked mainly at surveillance and inspection tasks in a study performed by Remote Technology Corp. EPRI's analysis, conducted by Battelle, Columbus Laboratories, focused on maintenance activities and attempted to identify potential availability improvements, as well as opportunities to reduce radiation exposure.

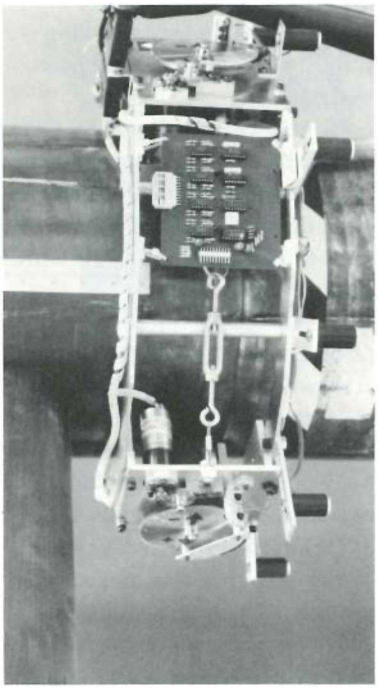
Each study attempted to quantify the cost in ORE and man-hours of a variety of jobs that a robot system might be capable of performing; the costs were then compared with those of the robot and its associated support systems and personnel.

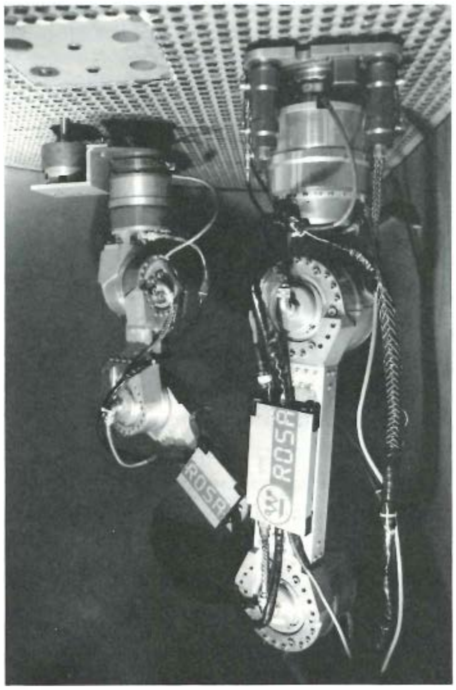
Surveillance and inspection tasks evaluated in the NRC study range from detection of steam or water leaks, verification of valve positions, and reading of gages to measurement of radiation levels in components and various methods of sampling to detect contamination. The EPRI study surveyed 22 tasks that are performed routinely or during refueling, including control rod drive maintenance, steam generator tube repair, and repair or replacement of various pumps and valves.

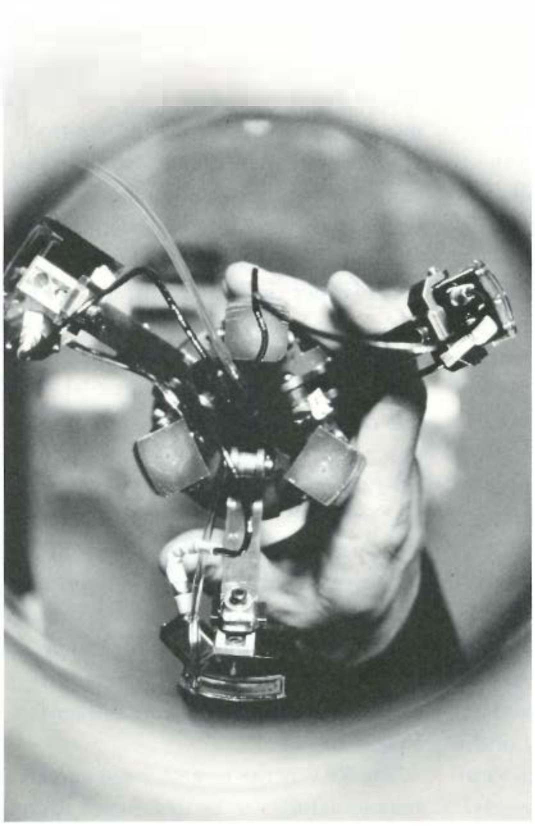
Although the scope of activities analyzed were different, both studies concluded there were potentially significant net positive economic benefits of applying robots in nuclear plants. The NRC study, based on application of a cost-benefit methodology to two existing plants, concluded that commercially available robotic technology can be retrofitted into existing plants and will reduce both radiation exposure to workers and plant operating costs.

The NRC study cautioned, however, that benefits can differ significantly among plants because of dissimilar design factors and operating histories. The report encourages utilities to perform plant-specific cost-benefit analyses, including consideration of all

Numerous robotlike automatic devices are used in the electrical utility and nuclear power industries for repetitive, special-purpose applications. These include remotely operated manipulators for the inspection and repair of steam generator tubes; automatic welding and pipe-cutting devices; and robotic pipe scanners for the detection of stress corrosion cracking.







costs of personnel entry into radiation areas, to determine whether robotic applications for such inspections are economical.

In the Battelle study for EPRI, potential maintenance applications were screened to identify candidate tasks common to many nuclear plants that account for a significant share of maintenance costs and are amenable to performance within the limits of current robotic technology. Follow-on cost-benefit analyses were performed for the application of robots to reactor cavity cleaning, health physics surveys, and flange unbolting/rebolting. Despite the amenability of these tasks to current robotic technology, it was concluded that none could be performed robotically without further technology development.

Using the net present value method, Battelle researchers found that robots for reactor cavity cleanup and maintenance bolting activities would pay back in less than one year, while health physics survey applications would pay back in about three years. The results were then tested with a range of values for outage time and radiation exposure costs.

Even with the lowest values ($700 per man-rem exposure and $300,000 a day outage time costs), robotization of maintenance bolting would pay back in slightly more than one year, while health physics survey tasks would require less than four years to pay back, the study found. Overall, the study indicated cost savings ranging from $100,000 to $1 million in net present value per robot, with the purchase price for each robot projected at under $200,000.

An important caveat noted by the Battelle researchers, however, is the limited availability of commercial robotic equipment geared specifically to nuclear applications. Because the nuclear industry has not been a major market for robot manufacturers, the business has generally been left to smaller entrepreneurial firms that can adapt robotic equipment for low-volume applications.

The nuclear industry thus needs some way to fund these developments or to attract entrepreneurs who are willing to financially shelter the technology during its demonstration phase, the study points out. This is in contrast to the situation in Japan, where a cooperative relationship between utilities and vendors has led to a more unified approach.

Prototype development

The core of EPRI's research in robotics is its participation in the development and testing of several prototype robot systems that could be forerunners of commercially available machines. Some of these robots could be used as transport vehicles to carry other robotic equipment, such as a flange unbolter or a steam generator tube-repair robot, into a high-radiation area, set up the smaller device at work, and then monitor its activity. Some, on the other hand, may be less capable of doing demanding labor, but could be used as intelligent master robots, controlling the work of stronger drones.

Several robot prototypes are making their debut in the recovery and cleanup of the damaged Three Mile Island Unit 2 nuclear plant in Pennsylvania, the site of a March 1979 loss-of-coolant accident that destroyed much of the reactor core and left large areas of the reactor containment building inaccessible to humans. Remote inspection has shown radiation fields as high as 3000 rad/h in some areas of the containment.

According to Adrian Roberts, a senior program manager in EPRI's Nuclear Power Division and manager of its TMI-2 information and examination program, the TMI cleanup effort has become a particularly strong spur to robotic equipment development. "At TMI we have a challenge for robotics that is here and now; some of the jobs simply can't be done other than remotely. And because we can't wait for the ultimate robot, we're taking advantage of work from a number of areas to develop robots that will get the jobs done. If robots are shown to be feasible for certain jobs at TMI, they can be applied at other nuclear plants."

Robots, in fact, have been tried at various times at TMI since the accident. In August 1982, a 25-lb (11-kg), remotely-controlled, tracked, tanklike vehicle supplied by DOE and called SISI (for system in-service inspection) was used to photograph and obtain radiation readings in areas surrounding the plant's water makeup and purification system. The water system's filters are highly contaminated with fission products from the primary core cooling system. The following spring, a six-wheel remotely-controlled device dubbed Fred was outfitted with a high-pressure water spray and used to decontaminate the walls and floor of a pump cubicle in the auxiliary building basement. Fred weighs in at 400 lb (181 kg); its mechanical arm can lift 150 lb (68 kg) and extend to a height of 6 ft (1.8 m).

The venerable Louie from Westinghouse Hanford has been brought to TMI to perform radiologic characterization during decontamination of the water purification system. Officially known as the remotely controlled transporter vehicle, Louie will be used to monitor radiation levels as the demineralizer resins in the water system are flushed out. Though the robot's nearly 1000-lb (454-kg) lifting strength will not be needed in this operation, its radiation-hardened television cameras will get a workout near the demineralizer tank, which has a contact reading of 3000 rad/h.

Perhaps the most ambitious effort to date to apply robotics in the TMI cleanup has been the EPRI-supported development by Carnegie-Mellon University's (CMU's) Civil Engineering and Construction Robotics Laboratory of the remote reconnaissance vehicle (RRV) to probe the basement of the reactor containment building. The basement level, where no human has entered in over five years, remains highly contaminated with the radioactive sludge left from some 600,000 gallons (2270 m^3) of water, including primary cooling water, most of which has since been pumped out.

The RRV, nicknamed Rover by GPU Nuclear Corp., the operating utility at TMI, has been assigned the task of entering the dark and damp basement by crane hoist, inspecting the scene with its three television cameras, and surveying the area radiologically with several on-board detection instruments.

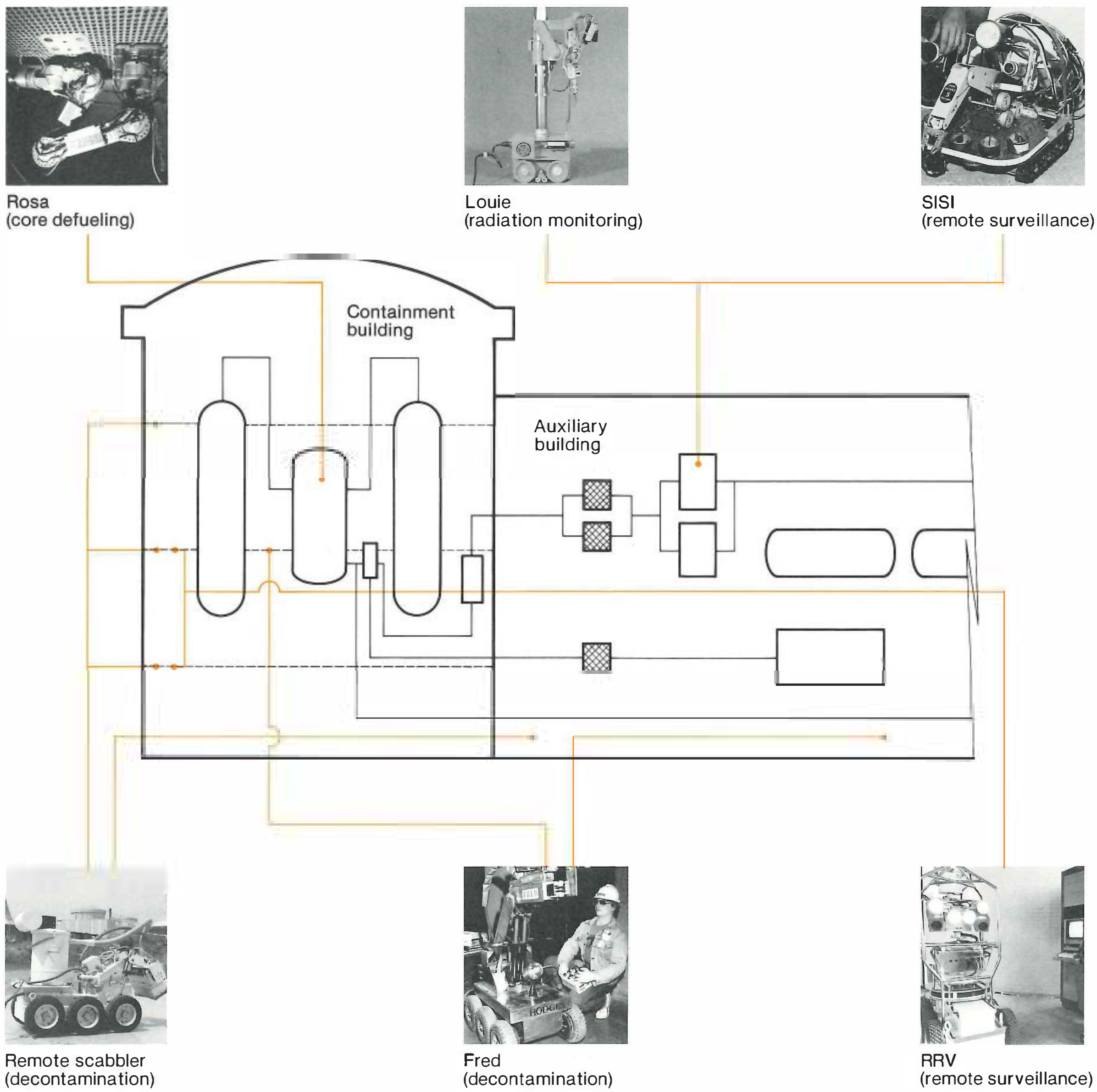
The six-wheel, 1000-lb RRV, developed in a cooperative effort involving EPRI, CMU, GPU Nuclear, DOE, and the Ben Franklin Partnership in Pennsylvania, was designed by CMU's William Whittaker, an assistant professor of civil engineering and director of the robotics laboratory. It features an innovative on-board umbilical reeling system designed to permit the vehicle to negotiate obstacles without dragging the umbilical. A stainless steel frame mounted atop the transporter base carries the umbilical reel, cameras, monitoring instruments, and control systems. The vehicle has also been designed for quick decontamination with water spray after it is removed from work areas.

A two-person crew controls the RRV from a console equipped with television monitors that is located a safe distance away from the hazardous area (at TMI, this distance is over 500 ft, or 150 m); one person steers the craft and manipulates the cameras while the other operates the umbilical reel. Teams of operators practiced maneuvering the RRV for several months along an improvised obstacle course in the adjacent turbine building (the staging area for much of the cleanup work) in preparation for lowering it into the containment basement.

The RRV is the first of three similar remote vehicles to be developed under

Robots at Three Mile Island Unit 2

Cleanup and recovery work at the damaged TMI-2 reactor in Pennsylvania presents a unique challenge for the application of robotics technology. Two remotely operated manipulators called Fred and SISI have already seen service in surveillance and decontamination tasks. The RRV, nicknamed Rover, has been assigned the job of inspecting the contaminated basement of the reactor containment building. A remote scabbling machine has been developed to remove contaminated layers from concrete floors. Louie, specially modified for the TMI work, is slated to monitor radiation levels as the plant demineralizer tank is decontaminated. Rosa, a versatile remote manipulator arm, has been proposed to lend a hand in defueling the TMI-2 reactor core.



the joint TMI recovery program. An important feature of the design is that the frame mounted on the chassis can be removed and other equipment added to the transporter. The second RRV base vehicle, modified by Pentek, Inc., EPRI's site contractor at TMI, is outfitted with a pneumatically powered scabbling machine and vacuum system for removing the contaminated top layer of concrete from floors in parts of the reactor building.

A third RRV remains at CMU's robotics laboratory for future development efforts. Other tasks proposed for future modifications of the prototype RRV include collection of liquid and sludge samples from the containment basement, collection of concrete core samples from the floor and walls, and some minor structural dismantling.

"At TMI the interest is in working vehicles with high strength, reliability, and mobility," explains Whittaker, the RRV's designer. "The challenges at TMI are very physical and active, and the equipment that will meet those challenges will be similarly physical and active. But there is certainly no one machine that will do it all, so we are looking at the evolution of a family of these things. One mode might be a fully configured RRV to supervise the activity of a drone that would carry tools only. Another possibility is a miniature version of the RRV that would operate radio-remote from the mother ship."

Clearly, robotic equipment is proving to be a valuable tool in the TMI recovery effort. Other applications of robots at the site are also planned. A manipulator arm built by Westinghouse Electric Co. and known as Rosa (for remotely operated service arm) has been proposed for use in the defueling of the TMI reactor core, tentatively planned for next year. Rosa, which can also operate underwater, is already known among some utilities operating pressurized water reactors for its ability to automatically inspect and repair steam generator tubes after it is mounted on the steam generator by service personnel.

Waiting in the wings

In addition to the robots that have been deployed at TMI, EPRI is evaluating two other prototype devices that could prove useful in nuclear plant environments. These machines could become cousins of the TMI machines in the robot family that Whittaker envisions.

One of these, produced by Advanced Resource Development (ARD) Corp., is known as an industrial remote inspection system (IRIS). Designed as a general-purpose surveillance and inspection robot for hazardous environments, IRIS is a relatively small (compared with the RRV) battery-powered, tracked transporter that can be equipped with optical, audio, and environmental sensors; manipulators; and communications and control subsystems.

The 200-lb (91-kg) IRIS features a unique high-frequency wireless communication system, specifically designed to operate in an environment cluttered with physical barriers, as well as with signal interference, which allows it greater mobility and range than most robots developed to date. A telescoping arm and a three-dimensional television system with zoom lens and microphones mounted on a pan-tilt pad bring the current payload to 70 lb (32 kg). Eventually, IRIS will contain some limited on-board intelligence, enabling it to retrace its steps backward even if normal control signals are lost or blocked by interference.

According to Floyd Gelhaus, an EPRI program manager who is evaluating IRIS and other robots for potential nuclear applications, the current ARD device has been designed strictly as a remote surveillance vehicle. "Its ability to do robust tasks is limited," says Gelhaus, "but the mobility and untethered configuration of the transporter, with its ability to carry various payloads, make it a valuable member of a robotics staff."

Gelhaus plans to have technicians at EPRI's NDE Center put IRIS through its paces before taking the robot into a recently constructed, nonradioactive plant environment sometime this fall. Duke Power Co. has agreed to host the testing activities at its new Catawba nuclear unit. The final step will be to test and evaluate the device in an operating plant.

Gelhaus is also considering possible applications for what is probably the most advanced robot developed so far—a six-legged, free-walking machine known as Odex. The Odex prototype, built by Odetics, Inc., "represents a remarkable breakthrough in its strength-to-weight ratio," comments Gelhaus, as it can lift more than five and a half times its 370-lb (168-kg) weight. Almost any other robot can heft little more than one-twentieth of its weight. "With that kind of power, there are a lot of potential applications," adds Gelhaus. Odetics has demonstrated Odex on videotape around the country, including scenes of it lifting the end of a compact pickup truck.

Because each of Odex's articulators, or legs, uses its own microprocessor, with a seventh computer coordinating overall movement, complex maneuvers are possible under the control of either an operator or a remote computer. The machine can pirouette 360° while simultaneously advancing in any direction. Its jointed legs permit it to assume six distinct profiles, ranging from a narrow stance for negotiating tight doors to a low squat. Odex is outfitted with twin TV cameras for visual transmission.

"Odex is a breakthrough in the state of the art," says Gelhaus, "but it will take some careful research to define applications for it in a nuclear plant." EPRI's work with Odetics has led to conceptual design modifications that will enable Odex to negotiate a power plant's internal obstacle course.

Future development

Technologically, Odex may be close to the fully autonomous, intelligent robot

THE EFFECTS OF ROBOTS ON ELECTRIC LOADS

In addition to the robotic applications research sponsored by EPRI's Nuclear Power Division, the Energy Management and Utilization Division analyzed the potential impacts of industrial robots on electrical loads. These could be significant, an EPRI-funded study by Science Management Corp. (SMC) found, in those industries and regions where robots are most likely to be used.

According to a 1981 study by CMU's School of Urban and Public Affairs, most robots installed in the future will be concentrated in the metalworking, machinery manufacture, and transportation industries. These industries account for half of all metalworking jobs in the United States and one-third of all manufacturing jobs; 90% of all assemblers work in these industries, as well as 70% of all machinists.

Robots will be used where industry locates its factories. Currently, half of all metalworking industry production workers are found in the five Great Lakes states (Illinois, Indiana, Michigan, Ohio, and Wisconsin), California, and New York. These states will likely continue to be home for the industries that will account for most of the robots installed by 1990, although some industrial capacity may shift from the Great Lakes and the Northeast to the sunbelt states.

How much electricity will robots require in the future? To answer that question, SMC first projected a range of installed robots by 1990, based on a number of analyses, and compiled robot nameplate power ratings from currently installed robots. This resulted in a projection of installed robots by 1990 ranging from 75,000 to 250,000, with a midrange projection of 121,000 robots. Aggregate nameplate power ratings range from 681 MW to 2.2 GW, with a midrange estimate of 1.1 GW. The last figure divided by 121,000 gives an average robot power rating of 9.24 kW.

SMC then made several assumptions to estimate the electricity consumption of such an installed robot force, among them that the robots are operated two shifts a day at 50% duty cycles and that industrial electricity demand grows at an annual average of 2% through 1990.

The analysis revealed that the low end of projected robot installations could mean annual consumption of 1.36 billion (10^9) kWh, or 0.16% of total industrial electricity demand in 1990. The high end projection of installed robots could consume 4.47 billion kWh/yr, 0.54% of industry's total electricity consumption. The midrange values would mean consumption of about 2.24 billion kWh/yr, or about 0.27% of total industrial use.

The average nationwide effect of robots on electricity use will be minimal. But as the study points out, the impact should be viewed from the perspective of individual industrial plants and specific utilities rather than from a national perspective. This was highlighted by the results of a comparative analysis conducted by SMC of the load at two manufacturing facilities where robots are already at work. The plants' electric loads were analyzed before and after robots were installed.

At an auto assembly plant, the addition of 62 spot-welding robots and associated equipment caused a 15% increase in kilowatt demand with a 17% rise in kilowatthour use. But the study found that only 44% of the increased power requirements were directly attributable to the robots; the remainder was used by conveyers and frame-handling equipment associated with the robots.

At a freezer manufacturing plant, the installation of four spray-painting robots produced increases in power demand and electricity consumption of less than 1%.

Although these results cannot be used to extrapolate effects nationwide, they imply that the entire robot system must be considered when evaluating the electric load impact of an installation. Moreover, specific robots used for specific applications can have a significant effect on plant electricity requirements. The study also found that several large robot installations in a utility service area may significantly improve a utility's load factor because of the robots' ability to work during off-peak periods. □

that researchers say would represent the ultimate marriage between machine automation and the developing field of artificial intelligence. Its ability to maneuver around or over obstacles under the guidance of a remote operator approaches the level of computer control integration that will be needed if a robot is to be capable of autonomously responding to a programmed set of directions by referencing a self-contained data base for its location, destination, route, and tasks.

Consummating the union between robots and artificial intelligence is a long-range research goal, however, because the challenges involve advancing the frontiers of computer modeling of solid geometry, as well as the structuring of large amounts of computer data for logical access by the robot. Various military and nonmilitary research programs around the country are now focusing on the mathematical and computer science aspects that will eventually be brought to bear on this challenge. The military programs are largely funded by the Office of Naval Research and the Defense Advanced Research Projects Agency. Others, including programs at Stanford University, Purdue University, the University of Michigan, the Massachusetts Institute of Technology, and CMU, involve nonmilitary as well as military-related R&D.

Irving Oppenheim, an associate professor of civil engineering at CMU, is working with EPRI on some aspects of the problem in a research project to assess the potential for applying artificial intelligence in robots for construction and maintenance work. The Japanese already make significant use of automatic devices for various tasks in construction, but, in general, these devices are not the smart type. Two elements that are needed to make robots autonomous, according to Oppenheim, are the ability to logically detect and avoid obstacles and a way of modeling the three-dimensional work environment of the robot so that its "world map" can be referenced as it proceeds on an assigned task.

"There are some attempts at the mathematics that will permit a robot to find a configuration that avoids an obstacle, and we are working with the existing ones, testing them out, finding their shortcomings, and modifying them to accomplish some of the objectives that these obstacle avoidance capabilities are going to have," says Oppenheim. "For example, we're testing whether a control algorithm can figure out how to command a robot to reach around two pipes, then reach in and touch a third pipe."

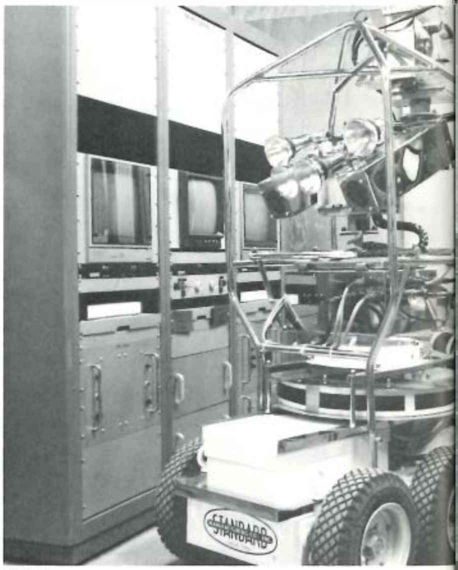
Progress in the second area of research—providing the robot with an accurate, three-dimensional model of its work environment—could someday lead to a robot's direct use of the original and as-built design drawings of an entire nuclear plant. Explains Oppenheim: "There must be a data structure, a computer program, that stores all the plant dimensions, the wall openings, solid areas, pipes, intersections, and so on.

"There are two approaches to this problem. One is to build a robot that has sensors all over it and simply keeps it eyes and ears open and doesn't touch anything. The other way is to somehow make use of all the dimensional data that have already been recorded and are on drawings and computer-aided design systems. We are exploring the kind of computer data structure that is best suited to the problem."

Designing nuclear plants with robots in mind is another area in which EPRI has sponsored research. Many of the difficulties involved in using a robot today stem from the fact that the plants were not built with such devices in mind; advanced reactor plants of the future will likely have special features specifically to accommodate surveillance or maintenance robots.

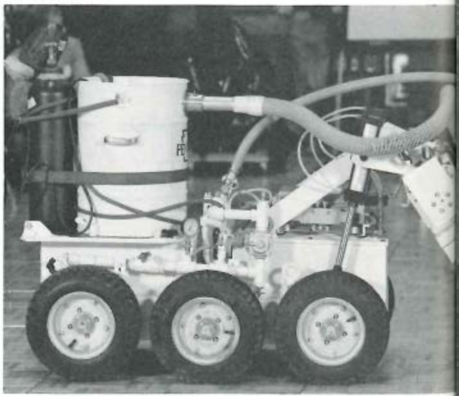
Under an EPRI contract, Westinghouse's Advanced Energy Systems Division studied the feasibility of using robots in a large-scale prototype breeder reactor. The analysis considered various routine and nonroutine maintenance and inspection tasks and outlined design factors that could enhance the applicability of robots. These include provision of adequate work and access areas, lighting and power outlets, and location of equipment and other potential obstructions.

As more special-purpose robots are developed for nuclear applications, the job of technically evaluating these devices with utility requirements in mind will also grow. EPRI's NDE Center may take on expanded responsibilities in this regard, having already participated



RRV

Scabbler



in the technical evaluation of IRIS. The center played host in October to a two-day seminar for utility engineers that brought many of the current state-of-the-art robots together for demonstration.

Breaking new ground

Directed R&D efforts and the immediate needs in nuclear power plants for reduced maintenance costs and lower occupational radiation exposure are breaking new ground in the application of robots to tasks with which most people would rather not be burdened. Despite the significant achievements to date, however, researchers caution that much more progress must be made before robots are seriously considered as reliable, economic tools. The entry of robots into the nation's nuclear plants will not occur rapidly, but a trend in industry thinking toward applying robotic equipment when and where it is feasible is already clear.

Michael Kolar, until recently an EPRI senior program manager who was involved in the Institute's study of robotic applications since the effort began in 1981, reflects the mixed viewpoints among many researchers in the field.

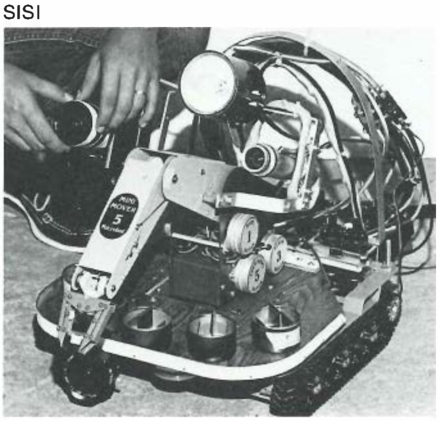
"There is some robotic technology that will let you do certain jobs, but it's not at all clear that you'll see many of these machines in wide use in the near future," says Kolar. "There are significant unresolved uncertainties, relating not only to the technology's hardware and software but also to other issues. Will the time required to train crews and execute a job with robots be short enough to be practical? That's not yet clear. NRC may decide to regulate some aspects of plant maintenance, and the role of robots in licensing issues has not yet been defined.

"Ultimately it will all come down to economics—are robots truly cost-beneficial?" asks Kolar. "Unless the costs of robot systems come down, or someone offers to provide them as part of a service package, I don't think we'll see widespread use of sophisticated robots soon. For EPRI, the issue is to ensure that good technology gets into the plants. But first, we have to find out what these machines can do. If we succeed, robots just might make it."

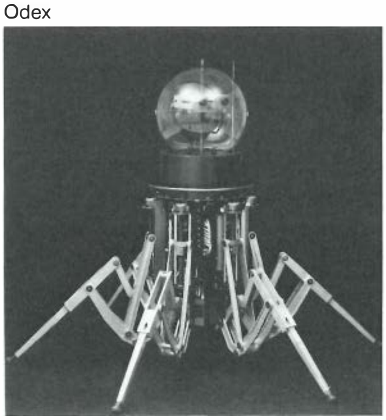
Utilities are expressing increasing interest in robots for nuclear plant applications, and as a result, the R&D community and the robot industry are responding with a range of devices and machine capabilities. The current activity represents a model of cooperative research, with both large and small companies, universities, government, and industry research groups working together to advance the technology. If recent success is any indication of the future, the outlook for robots to make a significant contribution to improved plant economics is encouraging. ■

Mobile robots are under development for general-purpose inspection and maintenance tasks in nuclear plants, such as visual and radiologic inspection and decontamination. These include the radio-controlled industrial remote inspection system (IRIS); the remote reconnaissance vehicle (RRV); the remote scabbler for decontamination, and Odex, a six-legged walking robot.

IRIS



SISI



Odex

Further reading

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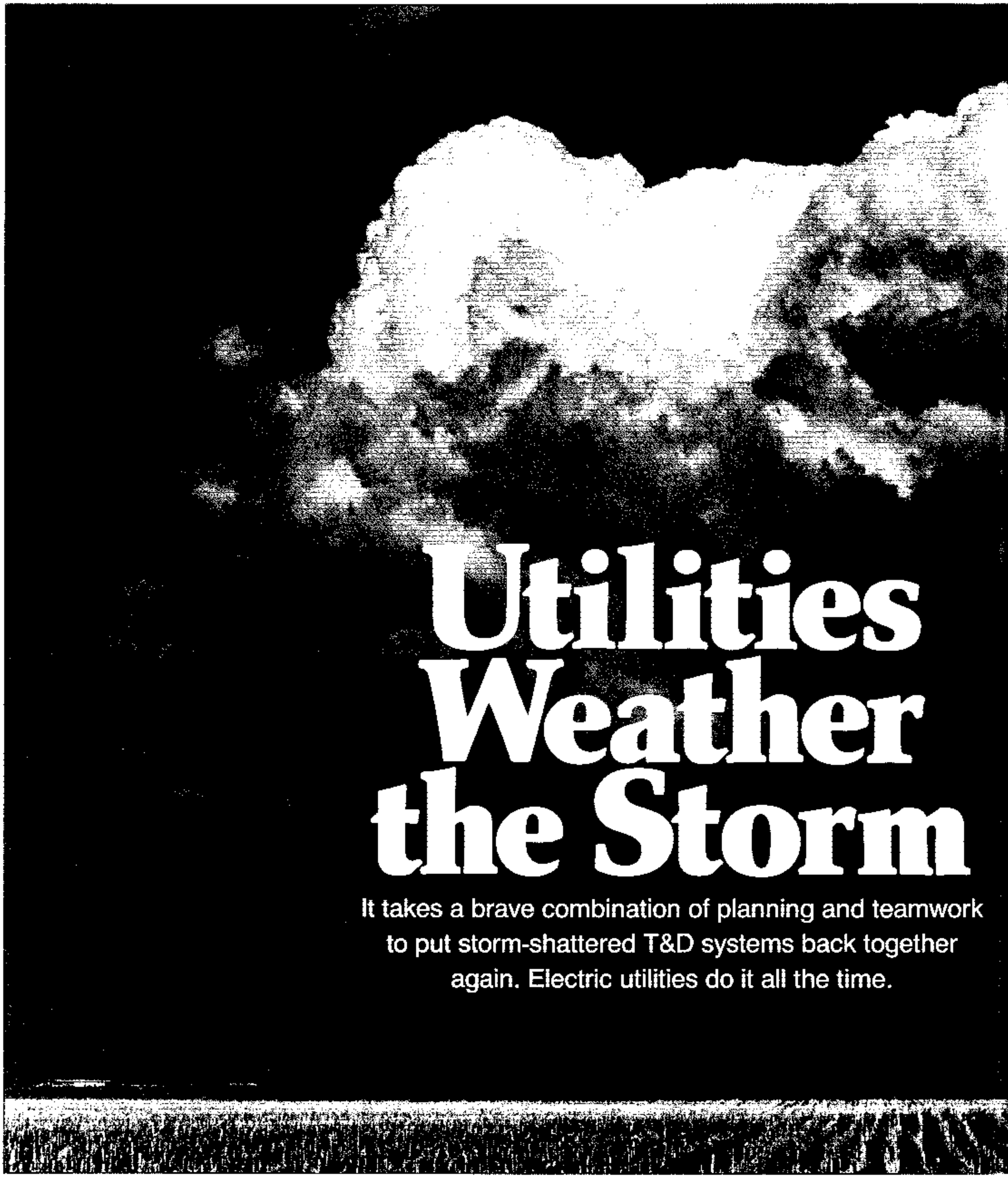
This article was written by Taylor Moore. Technical background information was provided by Floyd Gelhaus, Michael Kolar, Thomas Law, Adrian Roberts, and R. K. Winkleblack, Nuclear Power Division.



Utilities Weather the Storm

It takes a brave combination of planning and teamwork to put storm-shattered T&D systems back together again. Electric utilities do it all the time.

Utilities can't just talk about the weather—they have to do something about it. Transmission and distribution lines strung out across the country are easy targets for ice storms, hurricanes, thunderstorms, tornados, and blizzards; every year utilities lose millions of dollars of equipment to bad weather. And when the lights go out, utilities can't huddle indoors waiting until things blow over—they have to move as soon as possible to restore power to anxious customers.

Weather's assault depends on where a utility is located. For example, destructive thunderstorms that can jolt hundreds of distribution lines in the space of an hour tend to cluster on the eastern coast of the United States. Florida utilities in particular suffer from lightning damage, averaging as many as 100 thunderstorm days a year. Ice storms regularly pelt such states as Missouri, Georgia, and Alabama, where it can be too warm to snow but too cold to rain. The Gulf Coast states of Texas, Louisiana, Alabama, and Florida are the particular prey of hurricanes, and tornados can strike anywhere, although the tornado alleys of Arkansas, Oklahoma, and Kansas are likely places. In general, lightning storms, ice storms, and hurricanes are most feared because they damage large areas. Tornados, with their erratic touchdowns, are usually mercifully limited in frequency and in the area they affect.

Keeping a weather eye out

Whenever possible, utilities like to know what's blowing their way. Most receive detailed meteorologic forecasts via a dedicated circuit from the National Weather Service. These forecasts are basically the same reports the public gets from television or radio, as Richard Wagoner, operations chief for the National Weather Service at the service's Silver Spring, Maryland, headquarters, explains. Utilities often subscribe to commercial forecasting services as well, and some larger utilities have staff meteorologists to scrutinize reports and radar more closely. Even system operators who communicate hourly with neighboring systems on power purchases, sales, and the like, can and do pass along weather information. Besides predicting tomorrow's weather, these services alert utilities to ominous longer-term trends, such as a poor rainfall season in an area that relies on hydroelectric power or an unusually hot summer threatening a utility that buys much of its peaking power from other utilities.

Just like the rest of us, utilities have found that day-to-day weather can be capricious, and they may sometimes be as unpleasantly surprised as the stroller who neglects to carry an umbrella because last night's forecast promised sunshine. But unlike the casual stroller, utilities cannot afford to get wet, so virtually all utilities have carefully prepared strategies for when bad weather threatens. At one time or another, they all have had to batten down the hatches.

A good example is Houston Lighting & Power Co.'s response to Hurricane Alicia, which blasted into that utility's service territory on August 18, 1983. For three days the National Weather Service had watched Alicia gather strength in the Gulf of Mexico. It finally blew ashore at 135 mph (217 km/h), and before it left, about 750,000 HL&P customers were without power. Alicia had knocked more than 6900 spans of wire and 2350 poles to the ground. Fifty transmission circuits and 70 substations were out of service. Of 1100 distribution circuits, about 570 were knocked out. Three transmission towers were toppled.

But HL&P had tangled with Hurricane Carla in 1961, points out B. G. Burgess, general manager of system engineering, and the Texas utility was prepared with an emergency operation plan that told workers where to report and what to do before Alicia even came ashore. Supplies were earmarked in advance for the storm cleanup and had been delivered to specified areas; field repair vehicles and other equipment were waiting at prearranged locations. HL&P's Emergency Evaluation Center—ready for operation each year by the start of the hurricane season—was already assembled in the company's Houston headquarters, complete with system wall maps, an eight-channel radio, and telephones to gather and disseminate information on system operation and field restoration activities.

While Alicia felled power lines, knocked out distribution substations, and damaged power plants, dispatchers at HL&P's Energy Control Center struggled to keep electricity going to customers. And from the Emergency Evaluation Center, HL&P fielded what may have been the largest electric service restoration workforce ever assembled. Some 1700 HL&P crewmen were sent out into the fray, along with about 350 locally contracted crewmen, about 710 crewmen from other utilities across the state, and 250 tree-trimming crews. Together they did more than 2 months' work in just 2 weeks of 14-hour days, 7 days a week. Restoration cost $27 million, but it was accomplished in just 16 days. It paid HL&P to have a plan.

Killer hurricanes come along only once in a while, but bad-weather strategies often get a more frequent workout. Witness Pacific Gas and Electric Co.'s storm plan: During the past two winters, unusually heavy rainstorms drenched much of the utility's northern and central California service area, soaking the ground and making it unstable; strong windstorms knocked over pole after pole in the softened ground. Floods and mudslides finished the rout. Throughout the barrage of storms there were outages that affected anywhere from just a few to thousands of customers, and in one of the earliest storms in December 1982, two 500-kV transmission lines on the Pacific Intertie went down and briefly put 5 million customers out of service in three states.

But PG&E was ready for all that. At the utility's weather office in its San Francisco headquarters, meteorologists watched each storm roll in off the Pacific Ocean and gathered additional information through the National Weather Service, the National Meteorological Center, and a commercial information service. A network of dispatchers throughout the service area stood by waiting for the inevitable customer calls to come in. When they did, carefully trained repair crews were ready to restore power. Most outages were speedily corrected.

Another strategy is to adjust power system conditions as a storm becomes imminent in order to ensure the security of the electricity supply. One eastern utility that imports substantial amounts of power reduces imports as thunderstorms approach the service area, bringing its own—but more costly—generation on line instead. "That way, if a succession of line outages should threaten the utility's connections to the outside world, its own resources are immediately available," explains Robert Iveson, manager of the Power System Planning and Operations Program in EPRI's Electrical Systems Division. The additional cost of fuel for such short periods is relatively small, and well worth the customer security it buys.

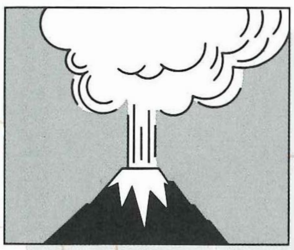
Helping hands

Teamwork is of special importance to a good storm strategy. "Most utilities, large and small, have agreements with neighboring utilities to exchange workers and equipment in times of need," says William Shula, manager of EPRI's Distribution Program. The utility on the receiving end typically foots the room, board, and travel bills. Sooner or later every utility needs a hand, and the goodwill of neighbors counts.

When Alabama Power Co. was hit by Hurricane Frederic in 1979, it took 21 days, 1000 Alabama Power linemen, and well over another 1000 linemen from Georgia Power Co., Gulf Power Co., Mississippi Power Co., Florida Power Corp., and various contractors to fully restore power. J. J. Thomley, manager of power delivery services, recollects that one of the most impressive sights he has

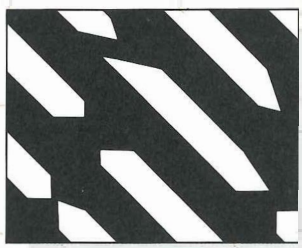
Meteorologists let utilities know in advance that a storm is brewing so repair crews and supplies can be readied. The National Weather Service and various commercial services issue detailed reports on upcoming weather; many utilities have in-house meteorologists as well.

Even volcanos can have weather-related effects. When Mount St. Helens erupted in Washington in 1980, volcanic ash blanketed distribution lines, insulators, and poles hundreds of miles downwind. This instigated poletop fires when it rained.

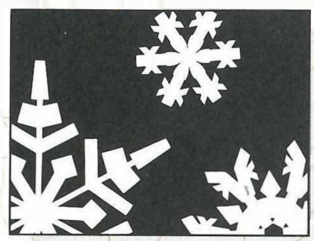


What the Wind Blows In

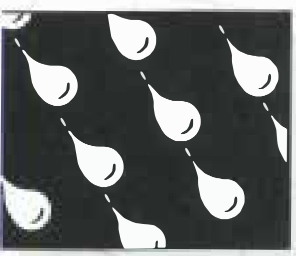
Ice storms can encase distribution lines in blocks of ice, and that weight can eventually bring the lines down. These destructive storms often strike near the Mason-Dixon line.



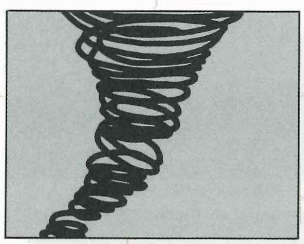
Snow may be pretty on postcards, but it can short insulators and cause trees to fall on lines. Heavy, wet snows can have the same effects as ice storms on T&D systems.



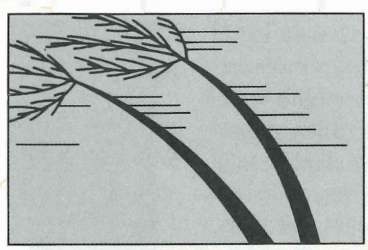
Thunderstorms regularly jolt East Coast power lines, particularly in summer. Extra lightning protection devices are often installed on T&D systems there.



Heavy rain and wind storms drench the West Coast every winter, knocking down distribution lines and sometimes even transmission towers.



Tornados don't inflict the widespread damage that some other storms do, but where they touch down they can easily demolish T&D lines, poles, and towers. Arkansas, Oklahoma, and Kansas are familiar with this kind of trouble.



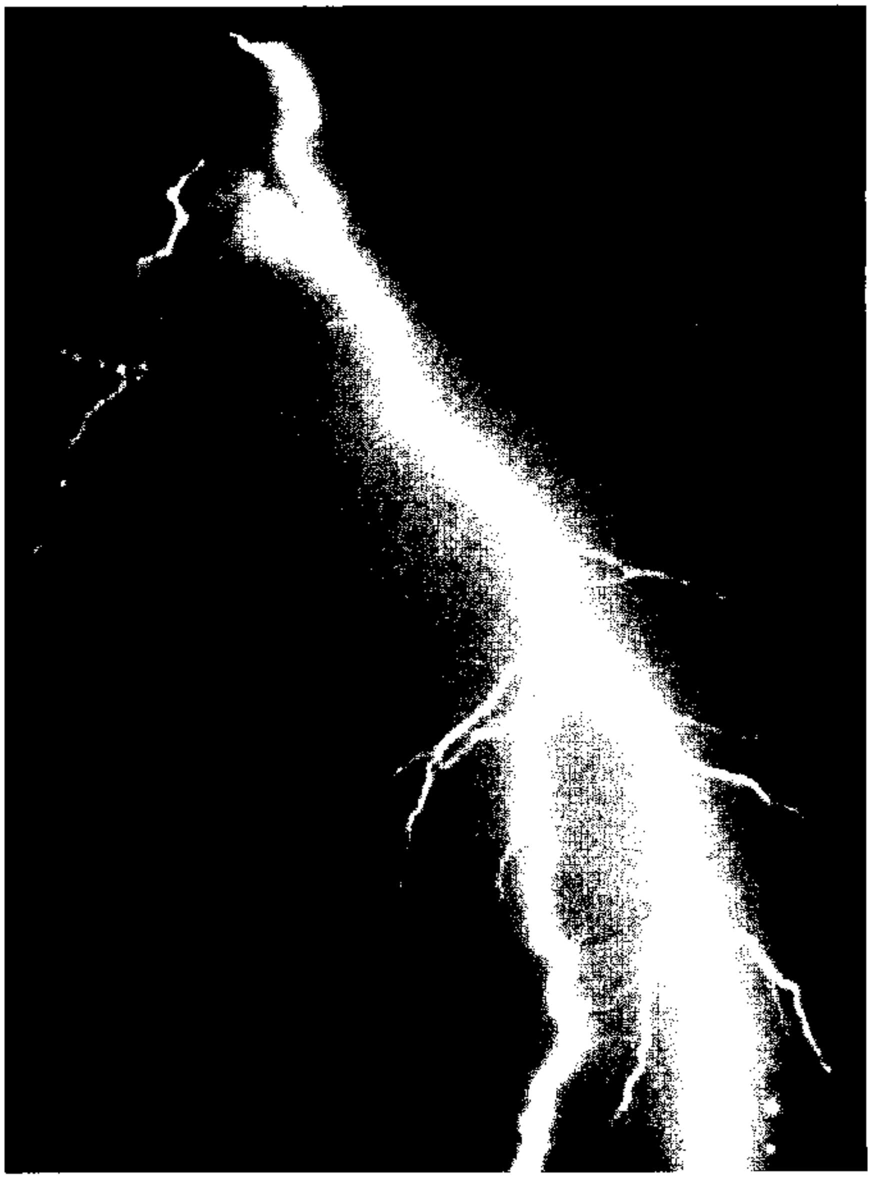
Hurricanes blow in off the Gulf Coast most autumns, flattening everything in their path. Utilities in Texas, Louisiana, Alabama, and Florida stand by with hurricane watch and repair programs.

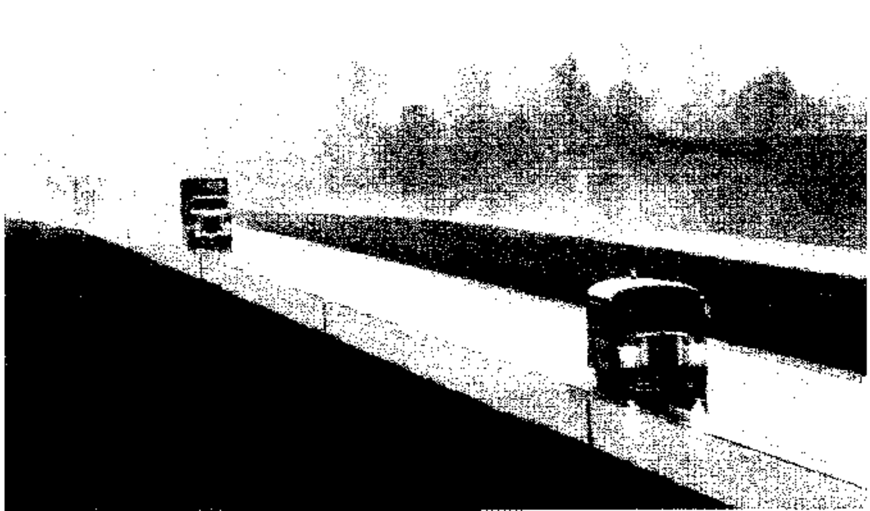
ever seen was that of the Mobile Municipal Auditorium on one of those dark nights when exhausted crews slept on cots and pallets on the floor, and a parking lot full of utility vehicles waited outside for the next morning's renewed efforts. Alabama Power's expeditious cleanup simply could not have been done without help.

When a utility has limited manpower at its disposal, teamwork is even more crucial. Verendrye Electric Cooperative counted on neighborly assistance in 1983 when a devastating ice storm hit this rural North Dakota coop, whose only assets are the distribution lines that bring electricity to its ranching and farming members. During the weekend of March 5 a freezing rain sheathed the lines with up to four inches of ice weighing as much as five pounds for every foot of conductor—three tons of ice for every 300-ft (90-m) span. Slumping under the weight of the ice and bulldozed by the wind, some 2200 poles went down, and 122 mi (196 km) of line lay on roads and farmyards. The icy rain then changed to snow, compounding the disaster. Some 1300 of the cooperative's 7300 customers were without power. It was unquestionably the worst storm in the cooperative's history.

Verendrye Electric immediately began splicing its system back together. The cooperative has a staff of some 50 people, about half of whom are qualified to do field work—not nearly enough to restore the shattered distribution system. Verendrye called on other North Dakota neighbors for help, as well as contract repair crews from as far away as St. Paul, Minnesota, 500 mi (805 km) to the east. At the height of the cleanup there were some 200 crewmen at work. The cooperative also requested additional materials, supplies, and equipment from as far away as Canada. Poles were especially hard to get on such short, desperate notice, recalls Manager Wally Beyer, and linemen were later to joke that the poles they received in the next few days were still steaming from the wood pre-

Much of the equipment a utility owns—lines, poles, towers, and substations—is exposed to the elements. When a storm hits, these investments are bound to take a beating. Careful design helps them withstand it better.





servatives applied in the factory. Eleven days after the first poles had toppled, service was fully restored to Verendrye's members.

Manpower and equipment are necessary to restore a battered utility system, but so is the whole-hearted cooperation of the local community, particularly in isolated rural areas. Grand Electric Cooperative, a small distribution system serving the northwest corner of South Dakota, was pounded by an ice storm in the spring of 1982, losing some 1300 poles, 65 mi (105 km) of line, and service to about 40% of its members. Crews and equipment from 24 other coops came rumbling into Grand Electric's Bison headquarters to aid the cooperative's dozen or so linemen. But an extra helping of town spirit was necessary to feed and house the total of 175 workers: Bison, population 450, has only one motel, three small restaurants, and miles of open prairie in every direction. Buffalo, 60 mi (97 km) away and equally small, is the only other town in the service area.

General Manager Darrell Henderson proudly reports that the whole town did its share to make the crewmen feel at home. The handful of restaurants opened early and closed late to serve tired and hungry crews, and they packed them lunches to take into the field. Every room in the motel was taken by crew workers, so some of the locals extended the hospitality of their homes. Gas stations and other services extended their business hours as well. "It was an excellent community effort by an awful lot of people," emphasizes Henderson.

With that kind of cooperation, Grand Electric's cleanup took only five days, half the time originally estimated. But Henderson insists neighborly help is commonplace. In a lesser blizzard this spring, a Grand Electric crew was stranded for 30 hours in their truck by the blinding snow, only vaguely aware of their location. When the sky cleared a little, they radioed a few landmarks to utility headquarters. A local rancher was able to identify their refuge from the sketchy description, and the crew rode out the rest of the storm in the safety of his ranchhouse. "People in rural areas know they all have to pitch in to make it work," concludes Henderson. "We depend on each other."

Pompeii revisited

Sometimes, uncommon measures are required to deal with what weather dishes out. Many utilities in rural Washington State were momentarily caught off guard when Mount St. Helens erupted on May 18, 1980, adding clouds of volcanic ash to the usually ordinary weather. Grant County, nearly 250 mi (400 km) east of Mount St. Helens, was one of the areas hardest hit, and volcanic ash thickly blanketed the lines, insulators, and substations of Grant County Public Utility District, whose biggest weather worry is normally an occasional lightning storm.

Hurried tests in the utility's electric shop revealed that the ash was relatively nonconductive when dry but highly conductive when wet. If it rained, wet ash on utility insulators and poles could form a path straight to the ground, short out the circuit, and set the pole afire. Something had to be done, and right away. The PUD first acted to protect costly substation equipment. Substations were deenergized and crewmen used compressed air or water to remove the dust from the most heavily encrusted stations. The work was slow and tedious, and equipment and vehicle engines kept stalling in the blowing ash. Later in the week, Grant County learned that a few neighboring utilities had safely hosed down their equipment with high-pressure pumps without deenergizing the substations first, so Grant decided to use that approach, calling in the local volunteer fire department to help. After the substations were cleaned up, transmission lines were taken care of.

Several days later, rain completed the job by washing the volcanic dust off distribution lines, except in the towns of Warden and Moses Lake, where ash accumulations were the heaviest. Poletop fires began breaking out all over, keeping the utility and the fire department hopping. Douglas Hein, engineering and construction manager for Grant County PUD, remembers, "When it was raining in the evening, you could go out and see insulators flashing all up and down the street."

All the ash from that first blast was eventually washed away by either the rain or the crewmen. Most of the fallen ash has since been plowed under the surrounding farmland, but it powders up again whenever the wind blows. Grant County has since invested in a high-pressure washing system with a special nozzle that breaks up the outgoing spray into beads so that the substations can be hosed down periodically without being deenergized first. If Mount St. Helens blows again, Grant County PUD is ready.

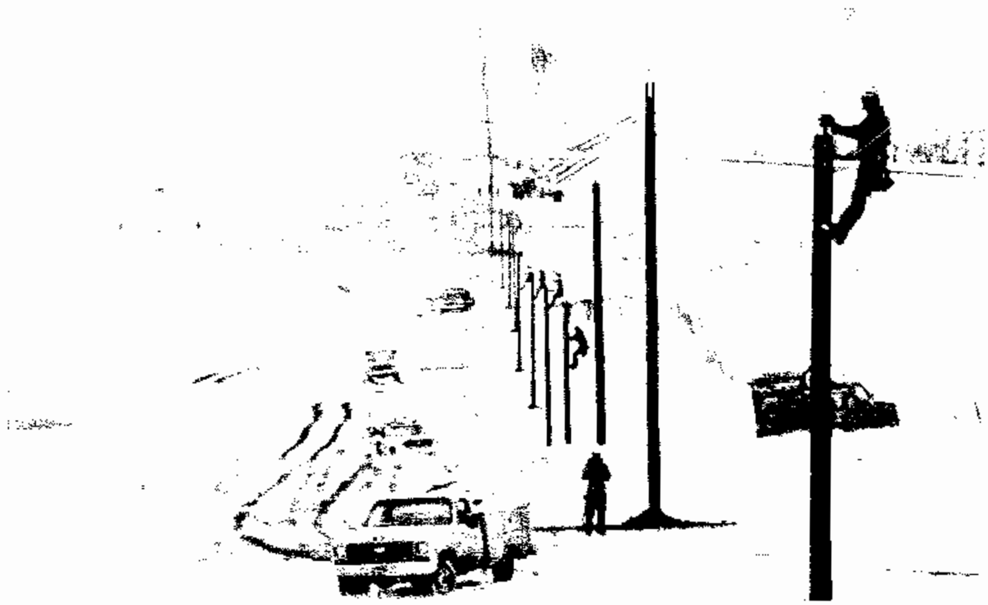
Sturdier T&D systems

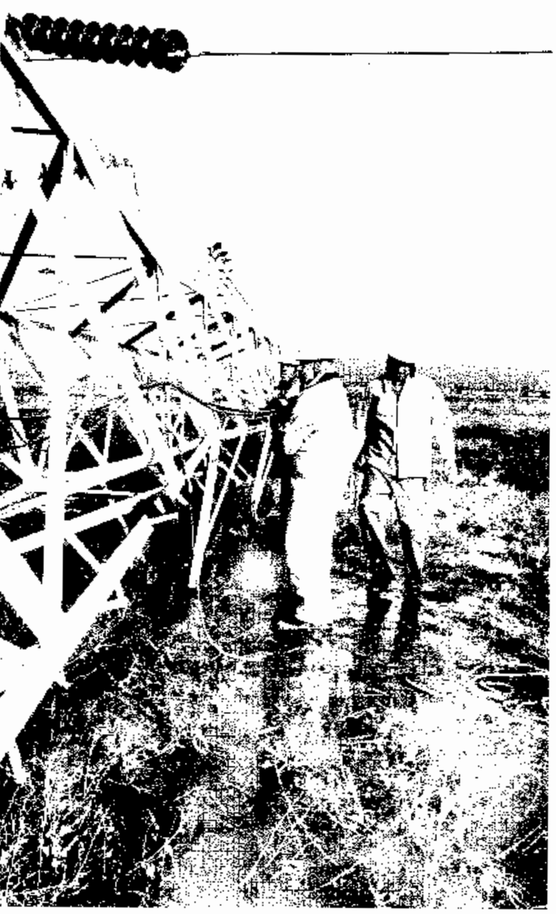
Strategies for dealing with hurricanes, lightning, ice storms, and tornados are necessities. Utilities can also brace themselves for the worst by modifying transmission and distribution system design to match the elements they are up against. All T&D systems must conform to basic National Electric Safety Code standards, but utilities build in extra strength and special protection whenever they feel it is warranted.

Many utilities do opt to selectively strengthen their systems. East Coast utilities, for example, have more lightning protection devices on their lines than West Coast counterparts, simply because they get more thunderstorms. But utilities do not want to overdesign, either. A system where every pole and every line can stand up to any freak of weather is beyond utility budgets. Much better is a happy balance. "Utilities will accept some damage, but not too much," sums up Kishor Mehta, an authority on wind engineering at Texas Tech University's Institute for Disaster Research.

To avoid both underprotection and overprotection, utilities need reliable data on the weather in their home service

Cleanup after a bad storm is business as usual for utility crews, and all utilities have strategies for getting the job done as quickly as possible. Nevertheless, it may take many exhausting days to fully restore a system after a devastating hurricane or ice storm.





areas. But these data often are not available. "For example, wind load is one of the most critical loads for which transmission line structures must be designed, and wind speed is the most important parameter in determining wind load," says Mehta. "But the extreme design wind speeds used in the National Electric Safety Code come from wind maps compiled with data from only 129 weather stations across the United States." This leaves a lot of utility territory unaccounted for and a lot of utility engineers guessing.

Hurricane data are particularly meager. Several years back EPRI and the University of Oklahoma developed something called BEASTIE—bifunctional EPRI atmospheric and structural test instrumentation equipment—to track down these data. The quick-attachment portable instruments can be placed on transmission towers in the last 12–18 hours before the predicted landfall of a hurricane to collect data on wind speed, wind direction, barometric pressure, temperature, and humidity. Each BEASTIE includes a microprocessor with its own power supply and tape recorder sealed in a leakproof aluminum enclosure.

EPRI sent 30 BEASTIEs to Oklahoma City: the plan was to wait for a hurricane warning and then deploy the devices to transmission towers in appropriate areas. But nature proved fickle, as Richard Kennon, manager of EPRI's Overhead Transmission Lines Program, explains. Wherever the BEASTIES were deployed, the expected hurricanes never materialized. "BEASTIE may be the best hurricane-protection method yet developed," jokes Kennon. BEASTIE is now being refurbished, and EPRI plans to try a new approach, scattering two devices at each of 15 different locations across the country to collect continental wind and hurricane data. Sponsoring utilities will be able to apply the data to their own design calculations.

Good data on how often lightning strikes a particular area are also in short supply. If a utility knew what lines or areas received most lightning, it could adjust its surge protection practices accordingly. "Up until now, the number of lightning strikes for a given line has been derived by a questionable relationship to the number of thunderstorm days a year in the service area of interest," says Herbert Songster, project manager in the Distribution Program. A more accurate approach would be to measure how many times lightning strikes the earth to provide a measure of how often lightning strikes a power line.

Because so many utilities are affected by lightning damage, many researchers have been studying the problem. Some years ago The Research Foundation of the State University of New York at Albany (SUNYA) installed a network of lightning locators, covering a substantial part of the northeastern United States. SUNYA is now working with EPRI to develop statistically correct maps of lightning strikes that utilities can use to optimize their T&D designs.

On-line lightning locators can also permit utilities to track approaching lightning storms and estimate their severity so that utilities can dispatch crews as needed into a threatened area (conventional weather radar cannot sense lightning). The EPRI–SUNYA network is configured so that interested utilities can subscribe to it as an on-line lightning tracking service, and two utilities, Baltimore Gas and Electric Co. and Philadelphia Electric Co., have already done so. Several other utilities are looking into this offer. At least three utilities (Tampa Electric Co., Detroit Edison Co., and Niagara Mohawk Power Corp.) already have their own lightning location systems.

Utilities are not only finding out when to strengthen their systems, they are also discovering new ways to do it. For example, EPRI has recently begun the search for an antiice coating for utility conductors. According to Project Manager Robert Tackaberry, Distribution Program, ice on lines takes the shape of an air foil, and as these air foils get bigger, they catch more wind, causing lines to vibrate violently up and down, or gallop. The weight of the ice and prolonged galloping will eventually bring the line down. A coating that would either reduce ice's adhesive strength or prevent ice from forming altogether could be of help to many utilities. Springborn Laboratories, Inc., a polymer science research group in Enfield, Connecticut, is now trying to develop such coatings.

Utilities have been—and continue to be—at the forefront of coping with weather. "In fact," points out Robert Iveson, "the quality of utility service has become so excellent that some wonder, 'Is it too good?' 'Is it better than the customer can afford?' The answer to those questions usually depends on when you experienced your last interruption, the conditions under which it occurred, how long it lasted, how much discomfort you experienced, and how much money it cost you." Most people would probably agree that when the power goes off, they'd like it back on as soon as possible. Thus, the research continues.

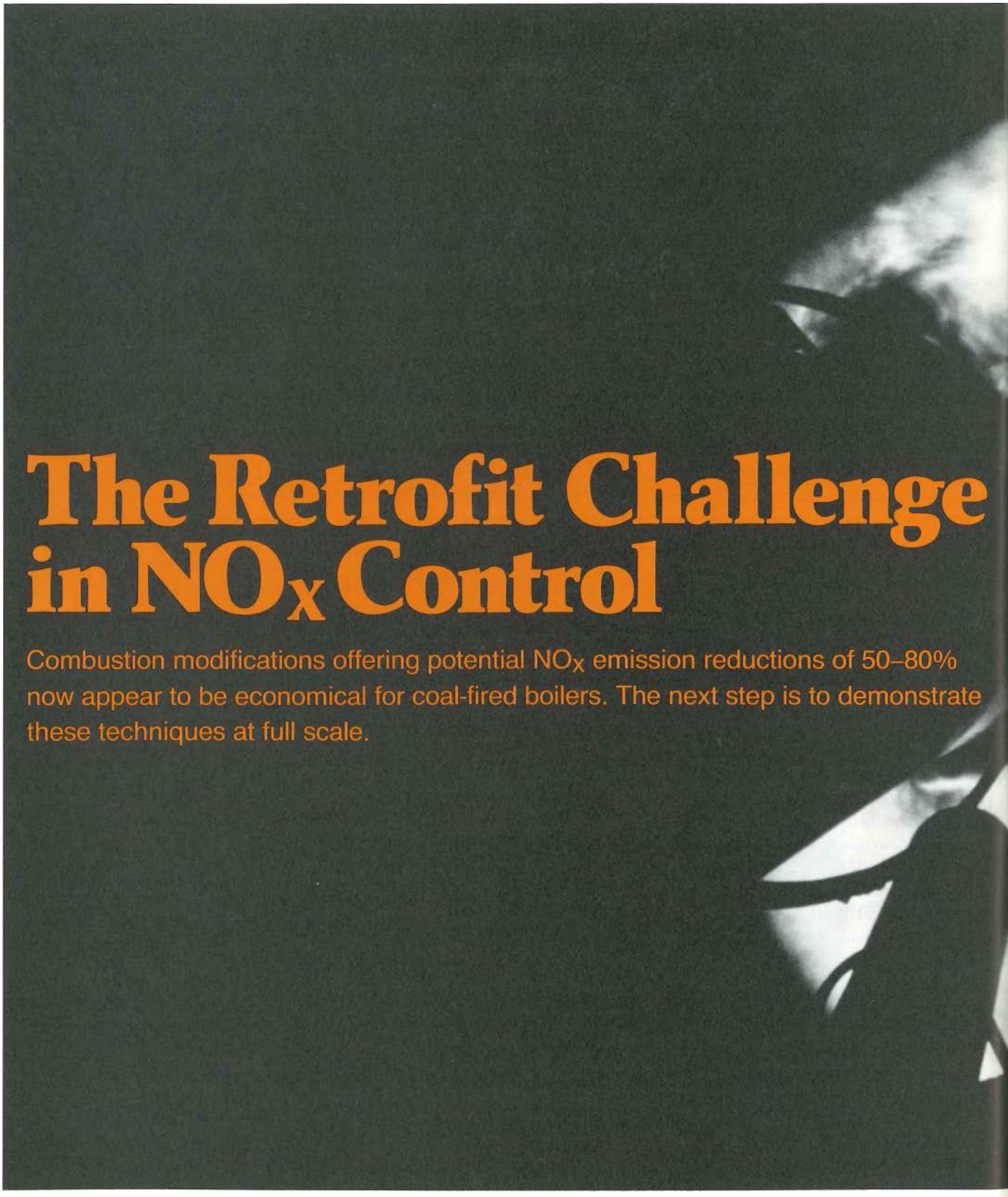
And so does the weather. If it is not lightning shorting out circuits, it is hurricanes blowing the system apart or ice storms flattening distribution lines. But through sound storm planning, dedicated teamwork, and design modification based on hard experience, the electricity gets delivered. Whoever said you can't do anything about the weather wasn't talking about utilities. ■

Further reading

Bethany Weidner. "When the Mountain Blew Up." *Public Power*, September-October 1980, p. 18.

Buddy Fischer and E. Philip Krider. "On-line Lightning Maps Lead Crews to Trouble." *Electrical World*, May 1982, p. 111.

This article was written by Nadine Lihach. Background information was collected through interviews with utilities across the United States. Technical information was also provided by Robert Iveson, Richard Kennon, William Shula, Herbert Songster, and Robert Tackaberry, Electrical Systems Division.



The Retrofit Challenge in NO_x Control

Combustion modifications offering potential NO_x emission reductions of 50–80% now appear to be economical for coal-fired boilers. The next step is to demonstrate these techniques at full scale.

Of the three main pollutants in coal-fired power plant emissions—sulfur dioxide (SO_2), nitrogen oxides (NO_x), and fly ash—NO_x is the only species that can be controlled without complex and expensive flue gas treatment. SO_2 and particulate ash are removed from the combustion flue gas with such technologies as scrubbers, baghouses, and electrostatic precipitators, which, though costly, can achieve reductions of 90% for SO_2 and in excess of 99.9% for fly ash.

Effective control of NO_x, on the other hand, requires intervention directly at the point of fuel combustion. Adjustments to the myriad interrelations of furnace fluid dynamics, thermodynamics, chemistry, and a boiler's specific operating and design factors can actually reduce the formation of NO_x during combustion, although at 50–80% the emission reduction levels are lower than those typically achieved for SO_2 and fly ash.

The need to control NO_x formation during combustion has had important implications for R&D. First, the variety of boilers in use by utilities today makes almost any hardware modification highly design-specific. Second, because combustion control requires fine adjustments and trade-offs in physical and chemical processes, scale-up of new configurations from pilot to full scale involves inherent uncertainty. In fact, even full-scale results are difficult to reproduce from one boiler to the next.

Although NO_x control techniques have been incorporated in new boiler designs, retrofitting such controls on existing boilers poses special challenges because they involve the very heart of the power plant. "It's very important that the consequences of a retrofit are fully assessed before implementing NO_x control measures so that boiler efficiency and reliability aren't impaired," explains David Eskinazi, a project manager in the Air Quality Control Program of EPRI's

Coal Combustion Systems Division.

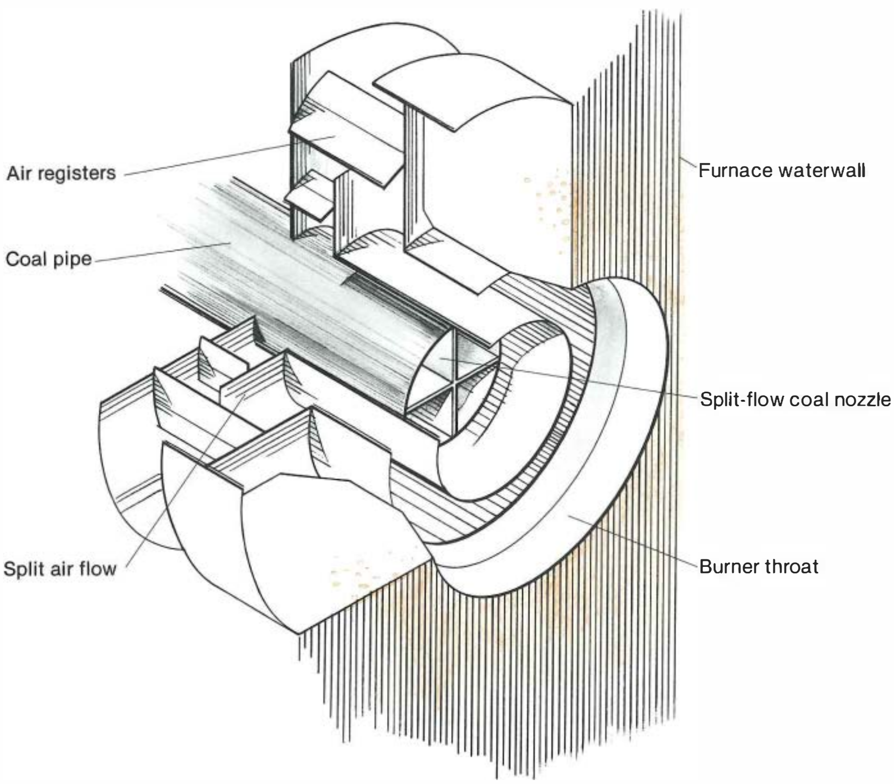
Despite these difficulties, significant progress has been made in recent years toward development of new furnace components and operating practices that promise to lower NO_X emissions by 50–80%. Retrofitting these changes to existing plants whose NO_X emissions are not already controlled appears possible at capital costs of \$5–\$20/kW, and costs for incorporating these innovations in designs of new units are even lower.

Growing focus on NO_X

The figures are encouraging news for the electric utility industry. Coal plants emit an annual average of 5 million tons of NO_X, nearly 25% of total nationwide NO_X emissions from man-made sources. Unlike SO_2 emissions, which have been declining moderately in most regions over the last 20 years, NO_X emissions have been on the rise, according to the Environmental Protection Agency, largely as a result of increased numbers of automobiles and other vehicles, which account for about half of total NO_X.

Recent analyses of atmospheric precipitation samples suggest that nitric acid accounts for about a third of total acidic deposition in the Northeast. Although the exact nature of the interaction of NO_X with SO_2, chemical oxidants, and the environment is not known, regulatory concern is beginning to focus on reducing total atmospheric loading of nitrogen compounds, as well as SO_2.

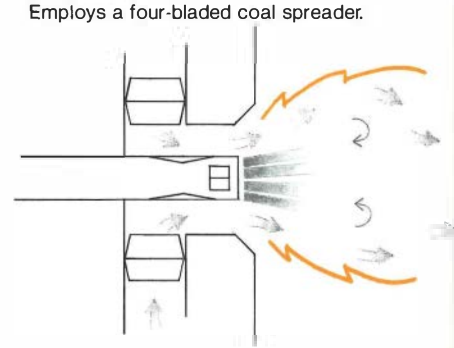
As a means of controlling NO_X emissions, federal regulations require power plants built since 1971 to meet tough New Source Performance Standards (NSPS). Initially, NO_X from plants built after 1971 was limited to no more than 0.7 lb/10^6 Btu released in coal combustion. Revised standards, which apply to plants built since 1979, take into account the varying properties and combustion characteristics of different coals—0.6 lb/10^6 Btu for bituminous coals and 0.5 lb/10^6 Btu for subbituminous coals. Some state and local regulatory agencies have imposed



Anatomy of Low-NO_X Burners

A variety of mechanical configurations are possible for controlling the mixing of fuel and air to reduce NO_X formation in a pulverized-coal-fired boiler. Burner manufacturers employ different approaches in hardware and design philosophy for different types of boilers. This generalized drawing of a low-NO_X burner incorporates features found in the various designs.

Controlled Combustion Venturi
(Riley Stoker Corp.)
Employs a four-bladed coal spreader.



even stricter emission limits.

To meet the NSPS, various combustion modifications were incorporated into the design and operation of more than 136 coal-fired boilers, representing some 71,000 MW of generating capacity. NO_X from these plants has been reduced by as much as 60%, compared with earlier designs.

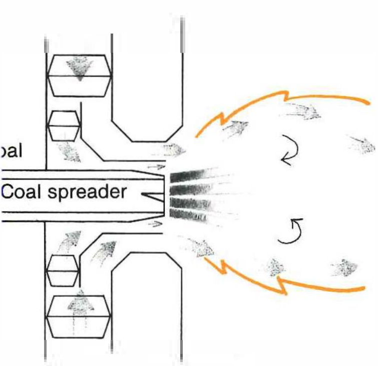
But about 85% of utility coal-fired NO_X emissions are from plants built before 1971 and are not now regulated. A mandate for broader NO_X controls would focus attention on retrofits for these older units, which total some 177,000 MW of capacity. "The potential application of the most recent NO_X control techniques to pre-NSPS boilers requires a significant development effort to integrate these processes within the various fixed physical and thermodynamic constraints of existing furnaces," says Eskinazi.

EPRI is playing a key role in that effort. "In conjunction with boiler manufacturers, the Institute is supporting the development and demonstration of a number of low-NO_X burner designs and advanced fuel-firing techniques, some of which are already commercially available," comments Michael McElroy, a subprogram manager in the Air Quality Control Program. "Beyond that, EPRI is continuing efforts to demonstrate these technologies at full scale to confirm commercial readiness and to expand their applicability to the widest range of operating boiler designs."

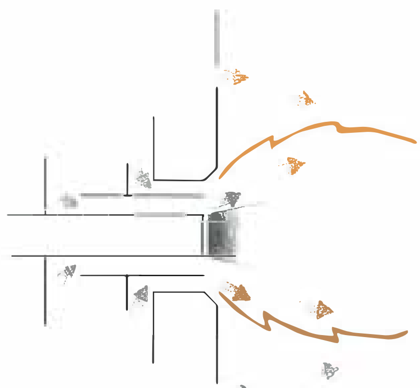
A variety of boilers

The formation of NO_X during combustion strongly depends on temperature conditions and oxygen availability, which, in turn, are strongly influenced by boiler design and firing configuration. Thus, some types of pre-NSPS boilers produce more NO_X than others.

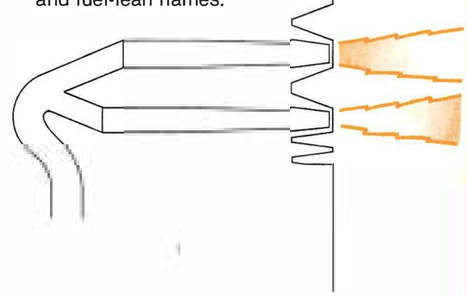
Tangentially fired boilers (inherently low-NO_X emitters because of their long, distributed combustion flame zones) account for about 30% of the total NO_X emissions from pre-NSPS boilers. Wall-



Controlled Flow-Split Flame
(Foster Wheeler Corp.)
Combines a split-flame annular coal nozzle with dual air registers.

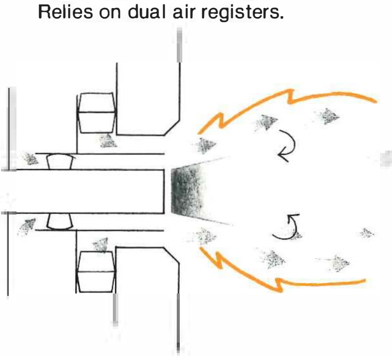


Distributed Mixing
(U.S. EPA)
Couples a low-NO_X burner with outboard air ports on the furnace waterwall.

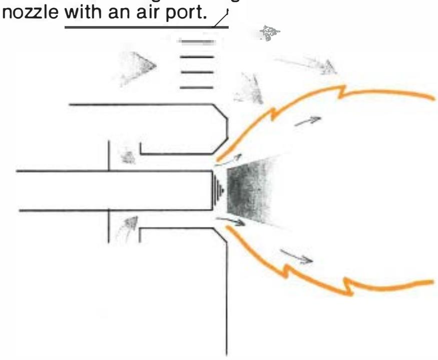


Tangentially Fired PM Burner
(Combustion Engineering, Inc., and Mitsubishi Heavy Industries)
Creates alternating fuel-rich and fuel-lean flames.

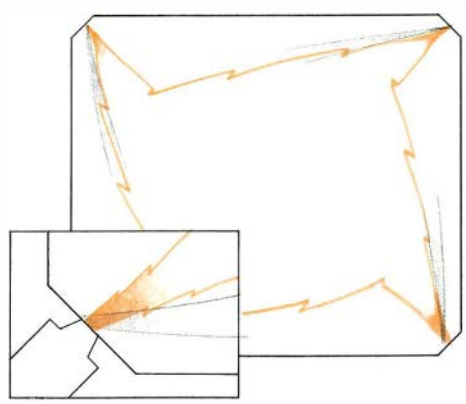
Dual Register
(Babcock & Wilcox Co.)
Relies on dual air registers.



Low-NO_X Cell Burner
(Babcock & Wilcox and EPRI)
Converts a standard two-nozzle cell burner into a single enlarged coal nozzle with an air port.



Concentric Firing System
(Combustion Engineering, Inc.)
Diverts some combustion air along the furnace walls away from the flame.



fired, dry-bottom boilers produce about 26%. Cell units, a different type of wall-fired design with burners arranged in clusters on the boiler wall, contribute nearly 15%. About 18% are from cyclone boilers, unique designs characterized by external combustion chambers in which a swirling flow of fuel and air is partially combusted before injection into the main furnace. All these boiler types are the focus of EPRI's R&D on retrofit combustion modifications because they account for the majority of NO_X emissions from coal plants.

Although postcombustion NO_X cleanup technologies do exist and commercial systems can be ordered, combustion process modifications are widely acknowledged to be the simplest and by far the least expensive means of controlling NO_X emissions. These range from relatively simple operational changes (such as reducing the quantity of excess combustion air) to more-extensive hardware modifications, such as low-NO_X burners, and innovative firing techniques with NO_X reduction potential of up to 80%.

Low excess air operation reduces overall oxygen availability, a requirement of any low-NO_X system. NO_X reductions of up to 15% and associated increases in boiler efficiency can be achieved with low excess air operation. The minimum practical excess air level, however, varies from one boiler to the next and can fluctuate with changes in fuel properties, generating load, firing configuration, and other factors. Low excess air operation thus requires a careful site-specific evaluation, including assessment of fuel and air balance within the furnace and the suitability of existing flue gas oxygen monitoring equipment and boiler control systems.

Overfire air operation is a hardware modification involving the addition of air ports in the furnace wall above the top row of burners. Some of the combustion air, typically less than 25%, is redirected above the burners to create a low-NO_X, fuel-rich primary combustion zone. Applications of overfire air, now in use on over 50 coal-fired boilers to meet NSPS requirements, have resulted in NO_X reductions of up to 30%.

Although the concept of overfire air operation is generally perceived to be fully developed from an engineering standpoint, most applications to date were incorporated into the design of new boilers rather than retrofitted. Overfire air retrofits may pose an entirely different set of design and operating requirements to achieve the full NO_X control benefit, while still maintaining high combustion efficiency.

New, better burners

Low-NO_X burners, which retard the conversion of nitrogen to NO_X by delaying the mixing of fuel and air in the burner zone, have been the central element of NO_X combustion control on many NSPS boilers. Each of the major U.S. boiler manufacturers now commercially offers a low-NO_X burner. Despite limited experience to date, the few commercial retrofits of these burners have demonstrated NO_X reductions of up to 50% at capital costs below \$5/kW.

The fundamental design concept of low-NO_X burners is to produce a less turbulent flame zone than conventional burners by delaying the initial mixing of coal and air and creating an oxygen-deficient primary combustion zone, which inhibits NO_X formation. Many options are possible to accomplish the desired combustion conditions. One approach divides the secondary combustion air into separate streams and controls airflow individually with a multiple-register system. Another technique employs special coal nozzles to regulate fuel-air mixing. EPA supported the development of another concept for wall-fired applications that involves a circular burner and air ports in the furnace wall surrounding the burner. Low-NO_X burners may employ more than one of these design concepts.

Although retrofit low-NO_X burners are now available for current commercial boiler designs—tangentially fired boilers and wall-fired boilers equipped with standard circular burners—there are no proven retrofit burners for cyclone-fired boilers or wall-fired boilers equipped with cell burners. These two design categories collectively account for about one-fourth of pre-NSPS coal-fired generating capacity and about one-third of NO_X emissions from pre-NSPS boilers.

EPRI's R&D in retrofit NO_X controls includes cooperative efforts with boiler manufacturers to confirm effectiveness and reliability of commercially offered low-NO_X burners, to expand their applicability to additional boiler types, to evaluate the full range of combustion controls and identify the most cost-effective mix of techniques for maximum NO_X reduction, and to develop new technologies where needed.

Pilot-scale tests of the PM burner for tangentially fired boilers, offered by Combustion Engineering, Inc., under license from Mitsubishi Heavy Industries in Japan, indicate NO_X reductions of up to 60%. An engineering feasibility study found that installation costs for the burner increase proportionately with the level of NO_X reduction required. For the specific retrofit applications studied, installed costs ranged \$8–\$15/kW for NO_X reductions of 45–60%. The PM burner is also applicable to new boiler designs at an incremental cost of about \$5/kW of generating capacity.

Riley Stoker Corp. has developed retrofit burners for wall-fired boilers. The company's controlled combustion venturi (CCV) burner has demonstrated considerable promise in field trial retrofits. EPRI has supported development of a refined design, and continuing R&D on the CCV burner may include a full-scale demonstration in combination with advanced air staging concepts.

To help ensure the availability of retrofit burners for the widest range of operating boiler designs, EPRI is supporting a cooperative effort with Babcock & Wilcox Co. to develop a low-NO_X cell burner for wall-fired boilers. Manufactured by B&W in the 1960s, wall-fired cell

POSTCOMBUSTION NO_X CONTROL

Beyond combustion control of NO_X, several postcombustion approaches have been proposed that may offer greater NO_X reduction potential. Among these, ammonia-based selective catalytic reduction (SCR) has received the most attention. SCR technology, installed on about 6000 MW of coal-fired capacity in Japan, where NO_X emissions have long been more tightly controlled, reportedly reduces NO_X in the flue gas by as much as 80%. A catalytic reactor between the boiler economizer and the air heater relies on ammonia to reduce NO_X to nitrogen.

But SCR is a complex process, and costs are an order of magnitude higher than more conventional combustion controls. The cost of fully developed SCR systems on new boilers runs about $100/kW; retrofit costs for existing boilers would be even higher. EPRI-sponsored pilot tests and an engineering-economic feasibility study indicate that SCR is not an attractive retrofit option for U.S. coal plants not only because of high capital and operating costs but also because of reliability concerns and other unresolved technical issues. These include uncertain catalyst life, waste disposal requirements, and the effects of ammonia by-products on plant components downstream from the reactor.

Other postcombustion approaches offering NO_X reductions of about 50% are under development, but their potential for application is also limited by high costs or uncertain reliability. These include electron beam treatment, selective noncatalytic reduction, wet scrubbers, and dry adsorption processes.

In addition to Japan, some European nations, particularly West Germany, are beginning to consider postcombustion forms of retrofit NO_X control because of increasing regulatory concerns about the environmental effects of NO_X and other emissions. Such developments could have possible ramifications on regulatory policy in this country. EPRI believes, however, that controlling NO_X during combustion, primarily with low-NO_X burners, remains the most economical approach for present use. □

burners characteristically have high combustion intensity, high heat release rates, and a compact burner zone, which result in high NO_X emissions.

The retrofit cell burner, developed to date at a pilot scale of 6×10^6 Btu/h, is designed to improve mechanical reliability over conventional cells and eliminate the need for pressure part changes during retrofitting by maintaining the existing burner throat diameter and spacing.

For two-nozzle cell burners, the new design diverts all the coal through one enlarged pipe in the lower of two burner throats, using the upper throat to supply a portion of the secondary combustion air. Pilot tests to date indicate a 60% reduction in NO_X with less than 1% unburned carbon. A full-scale demonstration, however, is needed to confirm emission reductions and improved mechanical reliability. B&W has also independently developed a dual-register low-NO_X burner for retrofit to wall-fired boilers equipped with standard circular burners.

Foster Wheeler Corp.'s controlled flow–split flame low-NO_X burner is also designed for wall-fired boilers equipped with standard circular burners. It reportedly achieves significant levels of NO_X reduction at costs comparable to those of other burner retrofits. The Foster Wheeler burner is among those for which EPRI is seeking host utilities for full-scale demonstration.

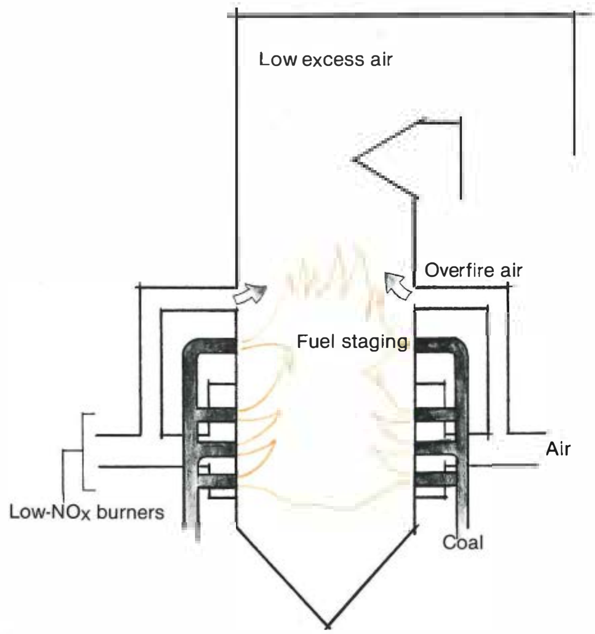
Integrating options

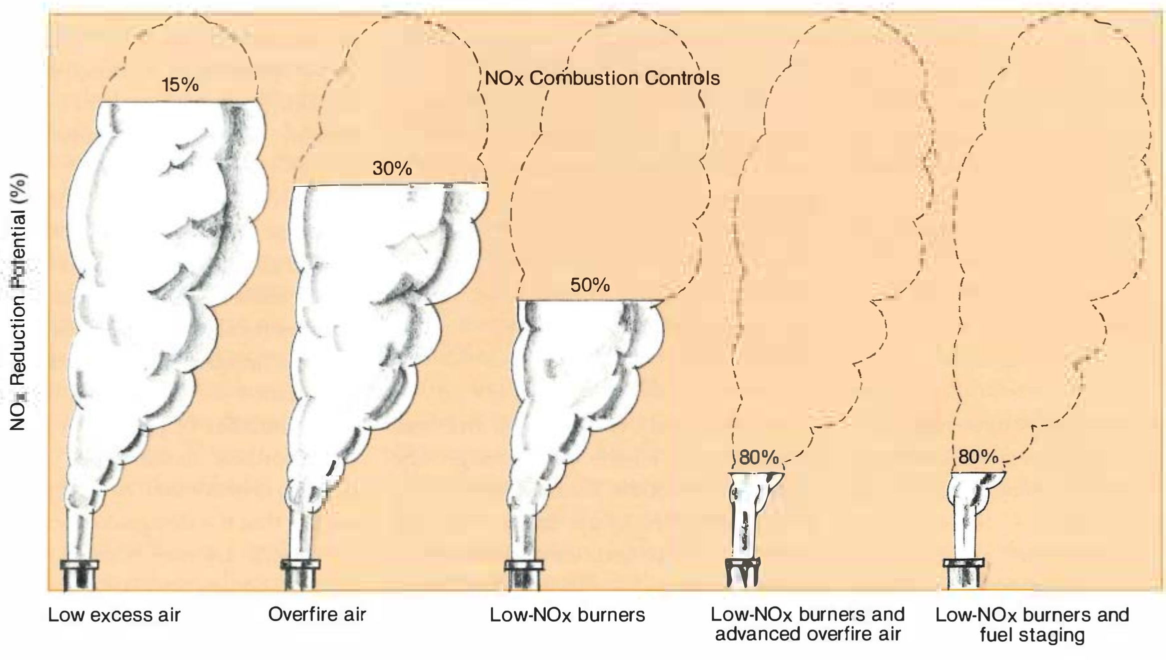
In addition to low-NO_X burners and conventional combustion process modifications, advanced concepts under development appear to offer further NO_X reduction potential through more-closely controlled fuel-air mixing, temperature, and combustion chemistry in the furnace. These include air staging, or advanced overfire air, and reburning, or fuel staging.

Advanced air staging is conceptually identical to conventional overfire air operation except that a greater portion of the combustion air (25–50%) is diverted above the burners to minimize NO_X formation. Reburning involves diverting a portion of the fuel stream (typically 10–20%) above the burners to create a fuel-rich zone and then injecting additional air to complete combustion. Advanced air staging and reburning can actually destroy NO_X produced in the primary combustion zone, in contrast to other techniques that simply inhibit NO_X formation.

The number of pre-NSPS boilers that are amenable to advanced air staging retrofits is uncertain. Although researchers feel that the design constraints affecting the inclusion of overfire air ports in existing boilers are reasonably well understood, the residence time requirements and mixing conditions for maximum combustion of the carbon in coal require further study. EPRI is funding laboratory- and pilot-scale tests to address these uncertainties.

The simplest and least expensive NOx control options involve operational or hardware modifications to produce conditions in the boiler that inhibit NOx formation. As indicated in this composite drawing, these include low excess air operation to reduce oxygen availability during combustion; overfire air operation, in which part of the combustion air is diverted above the burners to create a fuel-rich, low-NOx primary combustion zone; low-NOx burners, designed to control mixing of fuel and air in the flame zone; advanced overfire air operation, an extension of the conventional concept; and fuel staging, in which some of the fuel is burned above the main combustion zone. These approaches, alone or in combination, yield various degrees of NOx reduction.





In a recent pilot-scale investigation, EPRI and Riley Stoker used a 100 × 10^6 Btu/h test furnace designed to simulate the residence time and temperature of a utility boiler to evaluate combinations of NO_X control techniques. These included the use of low-NO_X burners with conventional and advanced overfire air designs and with reburning. Each of the arrangements was tested with four different coals.

Results showed that up to 75% reduction in NO_X was achieved with application of advanced overfire air operation and low-NO_X burners. Similar results were obtained for reburning coupled with new burner designs, although the significantly higher cost and complexity of the reburning technique, which involves more-extensive modifications to the furnace, cast doubt on its near-term retrofit potential for coal-fired plants.

The effects of different firing arrangements on carbon combustion efficiency were also studied in the test furnace and substantiated by limited field data. A qualitative comparison of the results indicates that given sufficient fuel mixing and residence time or, equivalently, enough distance between the main burner zone and the furnace exit, essentially all the fuel can be burned for any firing configuration, assuming temperatures remain high enough.

The test results highlight the importance of boiler residence time, furnace geometry, and a variety of physical and thermodynamic constraints in considering the full-scale application of a particular low-NO_X retrofit to a specific boiler design. "The question is under what conditions of boiler design and operation are sufficient fuel residence times available for each of the control options," adds Eskinazi.

To aid utility engineers in evaluating NO_X control systems, EPRI is sponsoring the development of a guideline manual that includes a methodology for screening the control options best suited to particular boiler designs. The work, derived from statistics gathered on some 700 operating boilers, is also intended to assist EPRI in determining boiler retrofit potential and in targeting specific design categories for further R&D. The approach considers NO_X reduction potential and cost trade-offs to indicate the incremental cost of various techniques. The manual is expected to be published in early 1985.

The next step

Although most low-NO_X combustion modifications have been demonstrated and accepted for new boilers to meet NSPS requirements, few pre-NSPS boilers have been retrofit with these control systems. And although retrofits appear to be technically feasible for a large segment of the pre-NSPS boiler population, long-term reliability of such retrofit measures has yet to be demonstrated. It is for this reason that having completed pilot-scale development work, EPRI is soliciting utility participation in full-scale demonstrations of several retrofit options for a number of specific boiler designs.

EPRI estimates that about 60% of coal-fired utility NO_X emissions are from boilers that could be considered candidates for some form of retrofit NO_X control. Estimates of retrofit capital costs for various control measures, including low-NO_X burners, range from $0.40 to $20/kW. For a given control measure, costs are highly site-specific, however, and can vary severalfold among different boilers of the same type.

Besides preserving high combustion efficiency, some of the major issues that have an effect on retrofit costs include possible effects on waterwall slagging and corrosion, boiler heat transfer, operating factors (such as flame stability, turndown, and load following), and site-specific structural considerations. Overfire air and advanced staging systems may require installation of new piping, ductwork, and furnace penetrations. Such technical issues are among those requiring full-scale tests for resolution.

Regardless of what new levels of NO_X emissions control are required in the next several years, experience to date indicates that new low-NO_X control systems can be successfully retrofit to many existing plants to meet the mandated limits. Completion of planned demonstrations and full-scale tests of these systems should answer the remaining questions regarding long-term reliability and impacts on overall plant operations. ■

Further reading

D. Eskinazi. "An Overview of Retrofit NO_X Controls for Coal-Fired Boilers." American Power Conference, Chicago, April 1984.

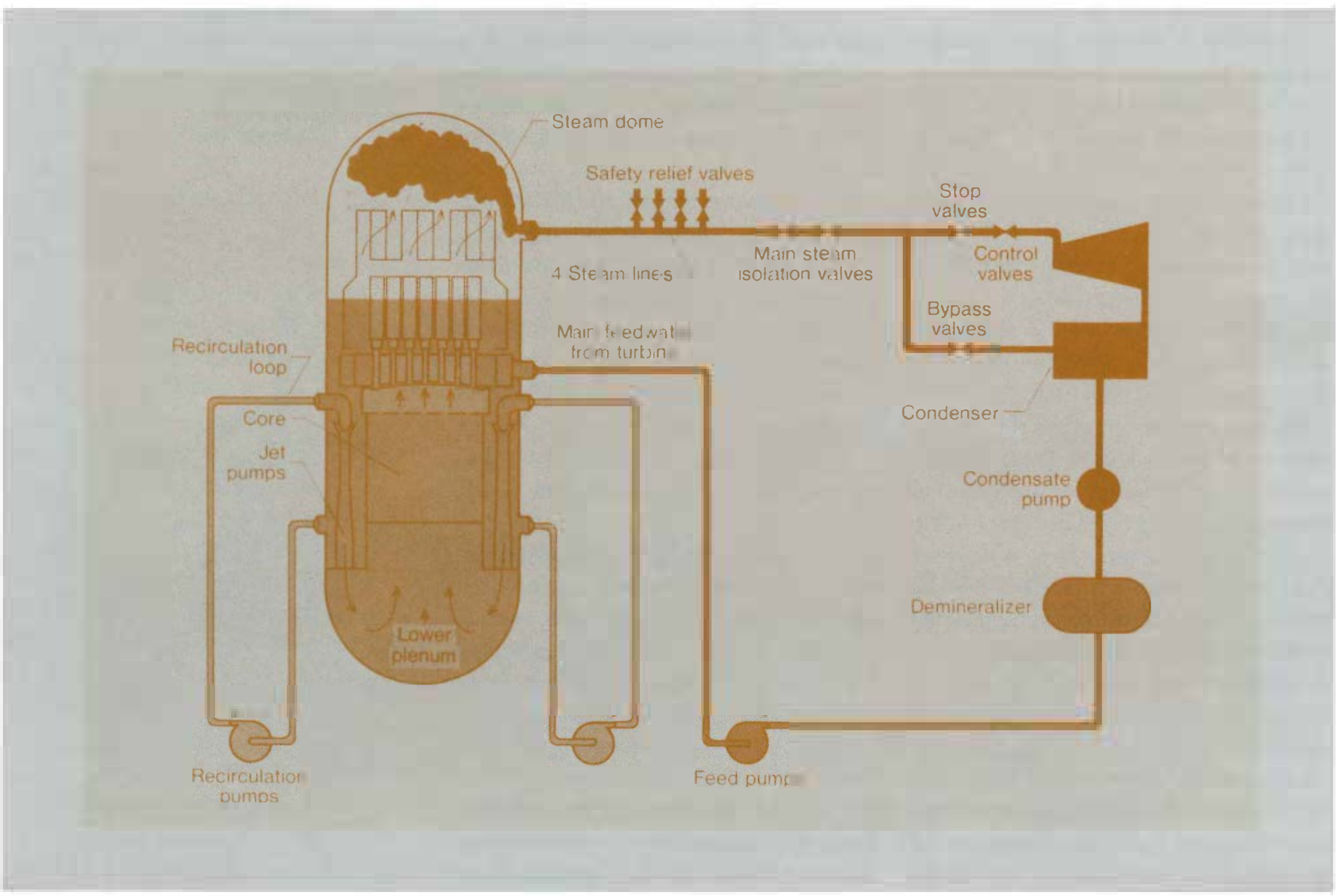
Proceedings of the 1982 Joint Symposium on Stationary Combustion NO_X Control, Vol. 1, Utility Boiler Applications. Conference proceedings, prepared by EPRI, July 1983. EPRI CS-3182.

M. W. McElroy. "Status of Retrofit Low-NO_X Combustion Control for Coal-Fired Utility Boilers." Air Pollution Control Association annual meeting, Atlanta, June 1983.

This article was written by Taylor Moore. Technical background information was provided by David Eskinazi, Michael McElroy, and Robert Carr, Coal Combustion Systems Division.

RETRAN: Code for Transients

Thermal-hydraulic simulation by the RETRAN computer code has become the industry standard for analyzing operational transients in nuclear steam supply systems.



The Nuclear Regulatory Commission has formally approved the EPRI code RETRAN, already an international standard for reactor transient analysis, for use in licensing submittals. A safety evaluation report (SER), the first granted to an EPRI code, allows utilities to refer to RETRAN in support of their applications for nuclear plant licenses and should greatly enhance their capability to respond to NRC questions on licensing issues.

The approval followed an extensive technical review of RETRAN by Argonne National Laboratory under NRC sponsorship and by a blue-ribbon design review panel under EPRI sponsorship. To keep the SER in force, the code is now being maintained under NRC quality assurance rules.

Before receiving SER approval, there was no assurance that NRC would accept a calculation made by using RETRAN. One of EPRI's goals in developing RETRAN was to obtain such approval, and utility members of the Utility Group for Regulatory Action (UGRA) helped obtain the SER.

During the late 1960s and early 1970s, computer codes for nuclear power applications tended to be relatively specialized; that is, they analyzed some particular system or problem. Various codes were available to analyze events in either the reactor core or the rest of the plant, but no code adequately covered both systems. For example, loss-of-coolant accidents (LOCAs) could be simulated only by making simplified calculations based on assumptions that had to be very conservative.

This multitude of codes resulted from the needs of the time. The codes were developed to meet a rapidly growing demand for design models of the large number of new reactors being built. The reason for this evolution was that vendors had groups of highly skilled specialists that focused on different types of analyses. They developed separate codes to answer the numerous individual questions that arose during the design of a nuclear power plant. In general, these codes were fairly simple and quick-running by today's standards because they were devoted to specific analysis and did not have widespread applicability.

As a result, calculations from these early codes usually presented only the boundary conditions of reactor safety or upper limits of performance, rather than an accurate simulation of complete plant response. Another disadvantage was that the codes generally belonged to vendors, not utilities, who usually had no way to verify independently the calculations made on their plants. Thus, a utility that chose a new vendor might encounter significant discrepancies between two vendors' models.

The use of these early codes in operator training sometimes proved misleading, because original analyses made for NRC licensing assumed the worst possible conditions. In most cases, calculated results were not representative of a plant's ordinary response, and operators lost confidence in engineering staff analyses. Consequently, operators sometimes responded inappropriately to actual transient events in their reactors.

To provide utilities with a more sophisticated code that could analyze transients more precisely, EPRI developed RETRAN, the first version of which was released in late 1978. The code was designed particularly for utility use in evaluating nuclear plant design and operation, evaluating plant safety, and supporting licensing requests. In addition, EPRI and its contractors needed a code to interpret experiments and analyses, to evaluate generic safety and regulatory issues, and to define new research objectives.

Since its release, RETRAN has become the industry standard for analyzing operational transients or hypothetical accidents in nuclear steam supply systems. It calculates best-estimate predictions by using detailed thermal-hydraulic simulation rather than on worst-case limits, which are based on overly conservative assumptions.

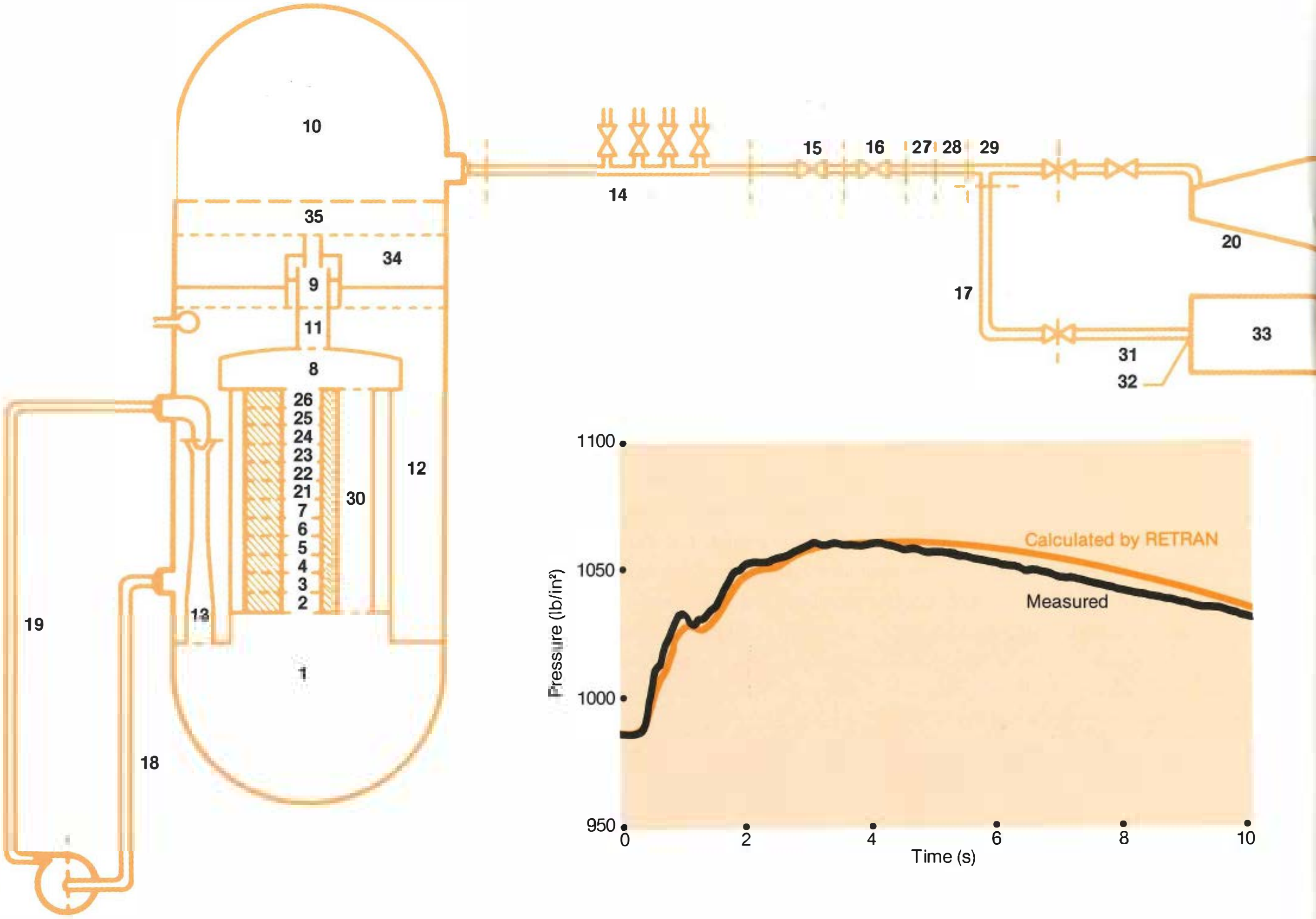
At present, EPRI has granted licenses for use of RETRAN to 45 U.S. utilities, 15 U.S. consulting organizations, 6 universities, DOE, and NRC. The contractor now working on the code, Energy Incorporated, had foreign rights to early versions of RETRAN and licensed 16 organizations abroad. International conferences to share information among RETRAN licensees are now held at intervals of about 1½ to 2 years. Since 1979 approximately 20 members of UGRA have been working to gain NRC approval of the code.

After the accident at Three Mile Island, investigators used RETRAN to simulate the sequence of events that occurred at that plant, as well as to examine several generic safety issues. Immediately after the accident, the code was used to determine possible methods of achieving cold shutdown (natural circulation only) of the reactor. Agreement between later RETRAN analyses of the accident and actual plant data has turned out to be quite good, and additional calculations have enabled investigators to separate individual events and determine plant response.

Other utility applications are extensive (WS-80-150, NP-2494-SR), but EPRI does not have access to detailed records of the full industrywide effort. However, EPRI has established a data base to collect newly available plant data and make them accessible in an organized form. Such data can greatly expand RETRAN use in new applications.

Several utilities have recently provided EPRI with analyses of RETRAN predictions against realistic plant data. In some cases these analyses have improved operating procedures and allowed discovery of unsuspected problems. For example, when General Public Utilities used RETRAN to investigate phenomena at a plant, personnel concluded that certain relief valves allowed flows at about twice rated conditions. This finding was later confirmed by experiments on an identical valve.

In another case, Northeast Utilities



Turbine trip tests at Peach Bottom Unit 2 provide an excellent example of RETRAN's ability to model thermal-hydraulic behavior in a full-scale BWR. The plant was modeled with 35 separate volumes for the simulation, 12 of them located in the reactor core. The transient was initiated by closure of the turbine stop valves, and a special data acquisition system took measurements throughout the plant at 6-ms intervals. Data on pressure in the steam dome show the very close correlation provided by RETRAN's simulation.

used RETRAN to predict plant response that matched data gathered during a transient caused by spurious control rod movement. The transient resulted in a 30% load rejection at the Connecticut Yankee plant in 1980. A report by the utility concluded that the code "is today the ideal choice for design basis and best-estimate accident analysis simulation."

The present version of the code, RETRAN-02, still has some important limitations, however, particularly in simulating a reactor system when the gas and the liquid in a two-phase mixture are not at the same temperature. Such conditions arise, for example, when cold water is injected into steam or when a pipe break causes steam and water to separate inside the pipe. A new, prerelease version of RETRAN addresses such problems directly. Research is also continuing on some remaining technical difficulties, related primarily to modeling the flow of a two-phase fluid in a reactor loop during a small break test.

"We now have a new version of the code, RETRAN-03, that will run much faster and provide nonequilibrium capability," says Lance Agee, subprogram manager of the Nuclear Power Division's Code Development and Validation Program. "This version should be available for utility prerelease testing in early 1985. It will require minimal changes to older versions. The new capabilities should greatly increase the number of possible RETRAN applications, especially with regard to small-break LOCAs." ■

This article was written by John Douglas, science writer. Technical background information was provided by Lance Agee, Nuclear Power Division.

Research for a Cleaner Environment

EPA's internal research program is the scientific base for many of the agency's regulatory decisions. The new assistant administrator for the Office of Research and Development outlines the agency's research agenda.

In a speech before the annual meeting of the American Association for the Advancement of Science on May 25, 1984, EPA Administrator William Ruckelshaus stated, "It goes without saying that science is the intellectual foundation of everything we do in EPA. Without firm empirical guidelines, our policies would founder. Science is the star we steer by. To shift metaphors, if our assessments of risk and our control measures are firmly rooted in a dispassionate search for truth, then we will continue to make steady, unspectacular but sustainable progress toward a cleaner, safer, more orderly and salubrious world, a world safe for man and for science."

The firm empirical guidelines Ruckelshaus emphasized are developed in the agency's research arm, the Office of Research and Development (ORD), headed by Assistant Administrator Bernard Goldstein. ORD serves as a resource for environmental and health effects information generated both inside and outside the agency. From his point of view as research manager for EPA, Goldstein offers that "the most exciting thing about this job is that there are scientists from so many different disciplines working on problems that cut across a wide spectrum of science. This job is not one for someone who likes to focus solely on one area of science."

As a trained physician and medical scientist who has chaired the Department of Environmental and Community Medicine at Rutgers Medical School and participated in various advisory groups, including EPA's Clean Air Scientific Advisory Committee, Goldstein brings the necessary versatility to the position. With his scientific background, Goldstein is also keenly aware of the specialized role performed by a research program in a regulatory agency. "The reason for research in an academic environment is to advance the frontiers of science. At EPA, however, we're translating that description of the research into one that's crucial to the mission of the agency."

From EPA headquarters in Washington, D.C., Goldstein's office does the strategic planning and budgeting for a research program of over $250 million per year. The FY85 ORD budget of nearly $306 million will fund research in more than 50 program areas.

Range of Research

The agency's 14 research laboratories, scattered from Rhode Island and Florida to as far west as Oregon, carry out ORD's research program. These facilities report to five program offices set up by discipline: health and environmental assessment, environmental processes and effects, environmental engineering and technology, health research, and monitoring systems and quality assurance. A sixth program office, the Office of Exploratory Research, manages the agency's exploratory research grants and university research centers program, both of which are supported through extramural funding.

In FY85 ORD will spend $193 million (or about 40%) of its research budget through contracts, grants, and cooperative agreements with organizations outside EPA's laboratories. Goldstein explains that the external research is funded through two mechanisms. "One supplies funds directly from the laboratories, where research is a direct extension of our internal programs. A second mechanism is carried out through a grants and centers program. We use this type of funding primarily to enlist the aid of the broader scientific community in generating ideas important and appropriate to the mission of the agency."

The exploratory research grants, approximately 15% of EPA's research budget, are awarded in four principal areas: environmental biology, ecology, and microbiology; environmental health; environmental engineering; and environmental chemistry, physics, and measurements. The research centers program directs funds to several universities, each of which specializes in a particular area, such as waste disposal, ecosystem management, groundwater, epidemiology, or hazardous waste.

Goldstein is reluctant to pigeonhole the relative roles of public and private environmental research, preferring instead the view that each sector follow its own research concerns—resulting in marginal redundancy but also in good interaction between public and private programs. "When I arrived at EPA, I was fascinated to see how many different

Goldstein

types of mechanisms there are that facilitate cooperation, from the very informal to the relatively formal. In fact, the private sector plays a major role in developing the extensive data base researchers use in the environmental sciences. There is no question that many of the advances in our understanding of chemicals in the environment, for instance, have come from work in the private sector. The more we know about the subject from anyone—regardless of research affiliation—the better off we are."

The value of outside research takes on even more significance in view of ORD's obligation to keep its research priorities closely aligned with the agency's working needs. Certain inherent tensions are a part of any regulatory agency, Goldstein points out. "The very best setting for doing research allows researchers all the flexibility needed to support those changes in direction that occur as the science develops. When some unexpected thing happens in the laboratory, possibly changing the course of research, the academic scientist can follow this new discovery."

Research in a regulatory agency can be quite different, Goldstein adds. "For example, researchers may plan research a few years in advance and proceed in a given direction. Then quite suddenly something new will develop. The Congress, the president, or other political forces will determine that dioxin or acid rain is an issue of extreme current importance. As a result, researchers may well have to stop what they are doing and begin something else. So you see, the flexibility is not so much in the hands of the individual researchers, but in the hands of the public to which any regulatory agency must ultimately be responsive. My job as a research manager is to be sure that when we do change direction, the changes are made for genuine priority items and the costs are fully recognized."

The $56 million increase in research funds for FY85 does not represent a substantial shift in priorities for ORD's research program. The increased funding will, however, strengthen the research programs in four high-priority areas of ORD's overall program: acid rain, hazardous waste and toxic chemicals, control technologies, and human health and risk assessment.

Acid Rain Research

Public and political pressure has made understanding the causes and effects of acid rain a top priority at EPA, as well as a topic of considerable interest to several other federal agencies. The Acid Precipitation Act of 1980 laid the groundwork for unifying the federal effort into a single national program—the National Acid Precipitation Assessment Program (NAPAP)—which is cochaired by EPA, the National Oceanographic and Atmospheric Administration (NOAA), and the U.S. Department of Agriculture. Twelve federal agencies currently participate in NAPAP. Funding for the program has increased significantly from $17.4 million in 1982 to over $55 million in 1985, with EPA's share currently over 50% of the FY84 funds of $27.6 million. As a component of the larger federal effort, EPA's acid rain research program falls into four main areas: source and receptor relationships, trends, effects, and mitigation.

ORD's source and receptor research focuses on developing an understanding of precisely which pollutants contribute to the acid deposition phenomenon and on attempting to determine which source locations affect a given receptor location. ORD hopes to obtain more data on the role of oxidants, such as ozone and hydrogen peroxide, as well as particulate matter and other aerosols that can act as reaction sites for acid formation. As a part of its research effort in this area, EPA is refining large-scale meteorologic models to better reflect the atmospheric processes governing the formation and transport of acid compounds. For instance, researchers are gathering data on the vertical rate of pollutant transport because it has a direct bearing on the horizontal transport rate and resultant dispersion of acid deposition and its precursors.

In support of its modeling work, EPA has successfully completed a field study that was able to track air masses across the northeastern United States by using an inert tracer to tag the air mass. The field experiment, called the Cross-Appalachian Tracer Experiment (CAPTEX), was a joint effort with EPRI, DOE, NOAA, and the Canadian government. CAPTEX has not only helped to advance tracer technology but will also contribute valuable information to a data base assessing the atmospheric transport and diffusion of pollutants for a regional air quality model.

Predictive models that show the effects of different emissions patterns, as well as calculations of the costs of alternative strategies, will build on the results of the source and receptor research. For example, ORD is involved in the development of an advanced utility simulation model (AUSM) to aid in evaluating the costs and emissions changes that would result from various strategies for electric utility emissions control. A state version of the AUSM model was completed in 1983, and work is under way on developing a national version.

Most of ORD's work in trends research involves collecting and evaluating data that will allow a look at longer-term acid deposition rates. EPA and other federal agencies are studying such indicators as tree rings, lake sediment cores, and acidification damage to tombstones because directly measured historical data are insufficient to extrapolate acid deposition trends in the United States. However, networks of monitoring sites to collect direct data are being organized at regional, national, and global levels. Under NAPAP leadership, nearly 150 monitoring stations will use standardized monitoring techniques to provide a nationally coordinated mechanism for emissions data collection.

To aid in establishing quality assurance standards for monitoring the acid deposition, ORD published a manual on data documentation procedures and equipment operation and maintenance guidelines. EPA is also helping to establish a data base that will centralize access to acid deposition data collected by all the monitoring networks in North America. The Acid Deposition System (ADS) data base, set up at EPA's Pacific Northwest National Laboratory, serves as a source for annual inventories of available acid deposition data, as well as a basis for assessing long-term trends.

Another EPA research effort focuses on the susceptibility of the environment to the harmful effects of acid deposition and addresses the sensitivity of aquatic systems to increased acidity. The effects of acid deposition on a given body of water may depend on the body's size and depth, the rate at which water flows through it, whether it is fed by surface water or groundwater, and the neutralizing capability of the surrounding watershed. Various combinations of these factors can determine to what extent the chemistry of an aquatic system will be altered. To further this research, EPA will be expanding its National Lakes Survey, which has recorded the conditions of lakes over a wide geographic area. The survey will include records on the biologic impact of acidification on fish. Several assessments of the effects of acid rain will be published in 1985 and 1986 and will cover the tolerance levels for aquatic ecosystems, the economics of terrestrial effects, and the physical and economic damage to aquatic ecosystems.

To assist in mitigating the effects of lake acidification, EPA is assessing the economic and environmental feasibility of liming. Swedish experience has shown that adding lime to acidified lakes can aid in neutralizing acid waters and in restoring fish habitats. EPA and the Fish and Wildlife Service are studying liming in lakes in the Adirondacks and Maine. The research will determine whether and where liming is practical and will quantify both the benefits and adverse affects of liming as a mitigation technique. The Fish and Wildlife Service is also doing mitigation research with EPRI.

Hazardous Waste and Toxic Chemicals

A significant portion of ORD's research outside the acid rain area addresses the problems associated with hazardous waste and toxic chemicals. This research spans several ORD programs, with particular emphasis on hazardous waste control, groundwater protection, and risk assessment.

EPA's mandate for hazardous waste research comes from legislation authorizing the agency to establish national standards to ensure proper management, transportation, treatment, storage, and disposal of hazardous waste. ORD's hazardous waste research places particular emphasis on engineering and technology, followed by work in monitoring systems and quality assurance.

"Hazardous wastes can be controlled in three ways," Goldstein explains, "by limiting the generation of wastes, converting them to harmless substances, or burying them." Burial is becoming increasingly complex and expensive, and as a result, the next decade will see a transition from land disposal of wastes to increased reliance on innovative detoxification and destruction processes. One of the innovative treatments currently under investigation is high-temperature incineration of hazardous waste. ORD's Municipal Environmental Research Laboratory in Cincinnati, Ohio, is testing the reliability of several pilot-scale incinerators and evaluating control systems currently under development. The laboratory has also completed field testing a mobile incineration system that can be used for on-site disposal at spill sites or where hazardous wastes have been illegally dumped. In the mobile unit hazardous substances have been successfully incinerated at temperatures of 2200°F (1200°C) while meeting air emissions requirements and achieving destruction efficiencies of up to 99.9%.

Goldstein points out that adequate control of hazardous wastes also requires extensive monitoring of disposal sites, particularly uncontrolled or abandoned waste dumps. ORD research in this area has resulted in the establishment of a geophysical support program that will provide the agency's Emergency Response Team with methods of locating buried wastes and of identifying underground waste migration.

Control Technologies

Improved monitoring and detection of subsurface waste migration will play a crucial role in the protection of the nation's groundwater supplies from hazardous waste contamination. Groundwater supplies provide nearly half of the country's drinking water, as well as water used for irrigation and industrial purposes. ORD's groundwater research is primarily directed toward improving monitoring and prediction techniques.

The groundwater environment is not easily observable and can vary extensively over short distances so that monitoring of groundwater quality and of the movement of pollutants is difficult, expensive, cumbersome, and imprecise. However, research with the U.S. Geological Survey has helped to advance methods for geophysical sensing, including the use of metal detectors, ground-penetrating radar, and seismic techniques. Goldstein says that improvements are also being made in the use of early warning monitoring systems to detect pollutant migration before it reaches the groundwater supply. Monitoring hazardous waste will receive increased attention over the next decade as new products that could pose new risks to the environment and human health continue to enter the marketplace.

Research to improve groundwater contamination prediction focuses on the processes controlling the movement and fate of hazardous substances that escape into the subsurface environment. ORD researchers are developing simulation models to improve their ability to predict the environmental impact of subsurface pollutants. Data on chemical underground transport behavior, paired with data on geologic materials that affect pollutants in similar ways, will be the basis for the models. These simulation models will be an important step toward preventing future groundwater contamination.

Human Health and Risk Assessment

Risk assessment research is also a very important facet of ORD's program. Existing legislation requires EPA to review all new chemicals entering the market to ensure against unreasonable health and environmental risks. But despite the widespread use of risk assessment by regulators, the science of determining risk is in many ways still in its earliest stages.

One of the important obstacles to determining risk is that researchers cannot test humans directly for toxicity tolerance. Human data are used whenever they are available, but for the most part, scientists must rely on extrapolations of data obtained in animal tests. As a result of such obstacles, risk assessment is accompanied by uncertainty. ORD research in risk analysis seeks to reduce uncertainty wherever possible. Goldstein elaborates, "One of the new areas ORD is evaluating is how some of the advances in molecular biology might be used to develop a better approach to measuring human exposure levels to pollutants in the environment. Right now we have to rely on all sorts of surrogates for exposure. The newer techniques in molecular biology seem to promise that in the future, perhaps within a decade, we should be able to take a blood test and measure exposure by looking for markers in the blood chemistry. Our current tests are not inaccurate, but there is more leeway in terms of plus or minus than we like in our risk assessment."

Goldstein emphasizes that uncertainty is one of the most important reasons that a complete separation between ORD's work in risk assessment and the regulator's responsibility for risk management is important. ORD does not get involved in EPA's policy decisions, but it does take a leading role in ensuring that there is a consistency of approach in performing risk assessments.

ORD's work in risk assessment provides perhaps the best example of the symbiotic relationship of a research program in a regulatory agency. "We talk a lot about risk assessment from the point of view of what it does to help risk management. But from the research manager's point of view, risk assessment has another major advantage. The formal assessment process is where you really become aware of what the crucial uncertainties are that are driving the risk manager, and as a result, a much better picture emerges of what the research needs are."

Goldstein admits that when he came to EPA to head ORD, he thought he would be spending a lot of time on environmental crises. He has found instead that the most important contribution he can make is to ensure that the research planning focuses on the agency's needs. In judging the success of his tenure as administrator, Goldstein concluded that ORD cannot be measured independently of EPA but must gauge its success in terms of the agency's success in achieving what Ruckelshaus terms the "steady, unspectacular but sustainable progress toward a world safe for man and for science."

This article was written by Mary Panke, Washington Office. Technical support was provided by Michael Tinkleman, Washington representative, Energy Analysis and Environment Division.

EPRI Wins IR-100 Award for Insulation Process

The development of nonflammable vapor mist dielectrics has been named one of the 100 most significant advances in technology of the year.

EPRI was honored recently for a development in technology that could improve methods of gas insulation for electrical equipment. Vice President John Dougherty received the IR-100 Award during ceremonies in Chicago to recognize development of vapor mist dielectrics, an insulating agent that can provide several times the electrical strength of gaseous dielectrics now in use. The new dielectrics can replace conventional gas, liquid, or solid dielectrics for insulating electrical equipment.

Industrial Research & Development magazine made the award as part of its annual program to recognize the 100 products it considers to represent the most significant technologic advances of the year. EPRI's award is shared with the Empire State Electrical Energy Research Corp. (Eseerco) and with Westinghouse Electric Corp., which developed vapor mist dielectrics at its Research and Development Center in Pittsburgh in a project jointly funded with EPRI. Eseerco contributed $1 million to the effort.

Research conducted at the center resulted in the discovery that very dense mists of micrometer-size liquid droplets offer several times the electrical strength of the most widely used gaseous dielectric, SF_6. A surprisingly small quantity of liquid (approximately 300 cm^3) provides sufficient mist to fill a large, room-size volume.

The new dielectrics are nonflammable and have good cooling properties. The liquid droplets do not freeze easily. In contrast with currently used gaseous dielectrics, the vapor mist dielectrics need not be pressurized, allowing the use of a safer, lighter-weight container.

"EPRI anticipates that this new technology will be of use in gas-insulated equipment, such as valves, SF_6 substations, and circuit breakers," explains EPRI Project Manager Edward Norton. "It is also hoped that further research will open to us new avenues of approach for applying vapor mist dielectrics to large power transformers." Possible nonutility applications include the suppression of electrostatic charges in a variety of such hazardous environments as grain elevators, oil tankers, and rocket launchers. ■

DOE to Conduct Test at EPRI's Coal-Cleaning Facility

EPRI and the U.S. Department of Energy have announced a joint effort to test new coal-cleaning techniques that promise to offer a more economical means of reducing sulfur emissions. EPRI President Floyd Culler and DOE Assistant Secretary for Fossil Energy William A. Vaughan signed a multiyear agreement in Washington, D.C., to use the Institute's Coal Cleaning Test Facility at Homer City, Pennsylvania, to test a variety of advanced cleaning techniques.

DOE will spend $4 million in 1985 to install test modules adjacent to existing equipment. In addition to contributing the facility, space, and coal, EPRI will pay for modifications to accommodate the government's equipment and for electricity, process water, and waste disposal. The Institute will also provide operators and maintenance and analytic support.

Research will focus on cleaning the finest fraction of the coal size spectrum. Laboratory tests show that crushing coal to 28 mesh or finer frees greater amounts of sulfur and other impurities, but improved methods must be found to separate them efficiently from the coal. Because this coal is difficult to clean with conventional technologies, much of it is discarded at cleaning plants. DOE will install a number of experimental cleaning devices at Homer City to test new separation methods. When testing begins, one ton of coal, 28 mesh or finer, will be diverted from the plant's main cleaning circuits each hour and routed to DOE's test modules.

"The cooperative efforts of the government and the utility industry, working side by side in this project, could have a significant impact on the future use of coal in the United States," Vaughan said at the signing ceremony. "This activity could set the stage for a new generation of coal-cleaning techniques that could markedly improve coal's compatibility with the environment." ■

Conceptual Breeder Design Completed

EPRI's Consolidated Management Office (Como) has completed its first major project—a conceptual design for a large-scale prototype breeder (LSPB). Como believes the operating and economic features of the new design are so promising that it is worthy of a closer look by electric utilities.

Como was established in June 1982 in Naperville, Illinois, under the direction of Clark Gibbs, then vice president of Middle South Energy, Inc. The office has responsibility for planning, implementing, and managing the technical program of EPRI's new Advanced Nuclear Generation Department, the objective of which is to identify and develop advanced breeder and improved light water reactor systems. To date, research at Como has concentrated on the LSPB, which will be used in discussions with the Nuclear Regulatory Commission about breeder reactor safety and licensing issues.

The LSPB has several advantages over previous breeder designs. For example, the decay-heat removal system includes a passive, natural circulation system that can operate without power. No guard vessels are needed around primary components, and the out-of-vessel fuel storage tank has been placed within the containment building. In contrast with earlier designs, the reactor vessel head remains in place during refueling and the containment above the head is in an air atmosphere, making it accessible to personnel during plant operation.

Como plans to expand international collaboration efforts and to study other advanced nuclear plant designs, including designs for pool-type breeders. An agreement has already been signed with Japan's Federation of Electric Power Companies. ■

CALENDAR

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

NOVEMBER

28–29
6th Annual EPRI NDE Information Meeting
Palo Alto, California
Contact: Soung-Nan Liu (415) 855-2480

28–29
Seminar: Fuel Inventory Modeling
Washington, D.C.
Contact: Stephen Chapel (415) 855-2608

JANUARY

16–17
Regional Conference: Compressed-Air Energy Storage
New Orleans, Louisiana
Contact: Robert Schainker (415) 855-2549

FEBRUARY

26–27
Continuous Emissions Modeling, Guidelines Manual
Atlanta, Georgia
Contact: Charles Dene (415) 855-2425

MARCH

13–14
Regional Conference: Compressed-Air Energy Storage
San Francisco, California
Contact: Robert Schainker (415) 855-2549

20–21
Continuous Emissions Modeling, Guidelines Manual
Denver, Colorado
Contact: Charles Dene (415) 855-2425

APRIL

30–May 2
Hydro O&M Workshop and Seminar: Dam Safety
Boston, Massachusetts
Contact: James Birk (415) 855-2562

R&D Status Report
ADVANCED POWER SYSTEMS DIVISION

Dwain Spencer, Vice President

WIND TURBINE OPERATING EXPERIENCE AND TRENDS

EPRI's wind power research program seeks to promote the evolution and use of utility-grade wind turbines. Such turbines must be technically sound, cost-effective, reliable, and compatible with utility system operation. As a major program effort, EPRI is conducting field evaluations of current machines in order to understand the state of the art, assess the operating experience of a wide variety of wind turbines, develop test capabilities, obtain test experience on key machines, identify research activities that will contribute to the evolution of utility-grade wind turbines, and develop a technical information base. In RP1996-2, one of several EPRI field evaluation projects, the primary emphasis is the assessment of wind turbine operation and maintenance (O&M) experience. The project covers all major types and sizes of wind turbines under development for bulk power supply applications. R. Lynette and Associates, Inc., is the contractor.

Wind turbines are classified as either horizontal-axis machines or vertical-axis machines, depending on whether their axis of rotation is parallel or perpendicular to the ground. Wind turbines can also be classified on the basis of nominal power rating. This report will consider small machines to be those rated below 100 kW, midrange machines to be those rated between 100 kW and 1 MW, and megawatt-scale machines to be those rated above 1 MW. These rating classes are not intended to be rigid definitions, but to provide a convenient framework for describing the current state of the art.

At the end of 1983 there were an estimated 8000 wind turbines installed in the United States, of which approximately 3800 were rated 25 kW or greater and were deployed in wind power stations intended for bulk power supply. Nearly all these 3800 were rated below 100 kW. Only seven were megawatt-scale machines, and the first midrange machines were just emerging in product lines. Almost all the wind power stations have been built since 1981. The primary market has been California, which has had the most favorable economic incentives. This rapid growth is expected to continue for the next several years, with market expansion to other states. However, market trends will be influenced substantially by the prevailing tax credit climate.

The megawatt-scale wind turbines are precommercial, experimental horizontal-axis machines that have been developed largely under federal sponsorship. Because of their small number and their limited operating time (as a result of technical problems), these machines are still in the early stages of a long maturation period. In contrast, federal and state tax credits for renewable energy systems have enabled private entrepreneurs to install large numbers of small machines in the past three years. The rapid accumulation of operating experience has enabled these machines to mature much more quickly. Further, whereas there is only one government contractor still pursuing the development of megawatt-scale wind turbines, a thriving small-wind-turbine industry has emerged and its leaders are attempting to scale up their products to midrange ratings. These differences in the state of maturation must be borne in mind when reviewing O&M experience. Additional background on wind power development appears in the May 1984 *EPRI Journal* (p. 6).

Project scope

At the end of 1983, RP1996-2 was covering six megawatt-scale machines, one small vertical-axis machine, and a station with 50 identical small horizontal-axis machines. The early operating experience of these machines, which in most cases was limited by startup difficulties, is described in the project's first annual report (AP-3735). In the past few months many machines have been added to the project; Table 1 shows all the installations currently

Table 1
CURRENT SCOPE OF WIND TURBINE EVALUATION

Rating	Number of Units	Location	Evaluation Period
Horizontal axis			
40 kW	60	Altamont Pass, California	1984
50 kW	75	Whisky Run, Oregon Altamont Pass, California	1983–1984
65 kW	91	Tehachapi, California Altamont Pass, California	1984
95 kW	120	Altamont Pass, California	1984
100 kW	1	San Gorgonio Pass, California	1984
200 kW	1	Altamont Pass, California	1984–1985
2.5 MW	5	Goldendale, Washington Medicine Bow, Wyoming Solano County, California	1983–1984
4.0 MW	1	Medicine Bow, Wyoming	1983–1984
Vertical axis			
50 kW	1	San Gorgonio Pass, California	1981–1984
500 kW	1	San Gorgonio Pass, California	1984–1985

covered. EPRI is conducting negotiations to expand the effort still further.

The results presented here from the existing data base are believed to be the best available. As the data base grows, EPRI expects the accuracy of performance and economic projections to improve. The results are for small and megawatt-scale machines; extrapolations to the midrange are not appropriate. There are no field results as yet for midrange machines, which have only recently become available for service.

The approach used in RP1996-2 is to gather, analyze, and report O&M data from utilities, private developers, and manufacturers who have wind turbines under test or in commercial service. In selecting turbines for evaluation, the project team seeks to cover all major classes of wind turbines as they emerge, to obtain a meaningful statistical sample for each turbine type, and to identify cooperative turbine owners. The reduced data are used in determining the overall reliability of current wind turbines, identifying recurring problem areas and possible remedial actions, determining current O&M costs, and projecting reliability and O&M costs for mature wind turbines in the same classes.

A primary measure of wind turbine reliability is availability, which is defined as the percentage of time in a given period that a wind turbine is available to produce energy, regardless of whether the wind speed is above the turbine's cut-in speed. To project future trends, availability is often adjusted to eliminate outage time resulting from nonrecurring startup problems with a new product. The RP1996-2 researchers also use a variety of other standard reliability measures, such as mean time between failures.

Project results

Availability and O&M costs are key determinants of the cost of wind-produced electricity. Table 2 summarizes the results to date on the two wind turbine classes for which the data base is sufficient to ascertain trends. As the data show, the small machines have a better O&M history, which is the result of their more rapid maturation.

The availability and cost analyses are based on several key assumptions that have not yet been adequately tested in operational systems because of insufficient field experience. One such assumption is that the useful life of fatigue-related items (e.g., rotor blades, hubs, and drive train components) will be 20–30 years. Another uncertainty is whether the vibratory and atmospheric environment to which wind turbines are exposed is adequately accounted for in the failure rates used for projecting wind turbine reliability. By expanding

Table 2
AVAILABILITY AND O&M COSTS

	Wind Turbine Size	
	Small	Megawatt-Scale
Availability (%)		
Achieved	70–96	20–80
Potentially achievable[1]	95–98	95
O&M Costs (¢/kWh)[2]		
Achieved	1.5–2.5	2.0–4.4
Potentially achievable	0.7–1.0	0.6–1.2

[1]It remains uncertain what wind turbine capital costs are necessary for achieving these potential availabilities. Capital costs are trending downward, most rapidly for midrange machines.
[2]O&M costs are in 1984 dollars.

the data base and enabling component failure rates to be calculated on the basis of actual field experience, evaluation programs like RP1996-2 will determine the validity of the assumptions that have been made and will increase the accuracy of (and confidence in) these early reliability projections.

Key maintenance problems on the small wind turbines have involved braking systems (malfunctions and excessive wear), hydraulic leaks, corrosion and soiling, control logic defects, and structural failures. The megawatt-scale machines are considerably more complex; Figure 1 shows their maintenance requirements by major component type. It is generally believed that existing engineering practices are adequate to deal with all these problems except structural failures.

Although some wind turbine structural loads are fairly well understood, loads stemming from wind turbulence and the complex behavior of wind in the vicinity of a turbine rotor are not. There are no wind models or load prediction models that satisfactorily address all aspects of wind turbine design. Hence wind turbine designers have relied on extrapolations from loading experience with earlier machines or on hypothetically generous structural safety margins with attendant cost penalties. The risks in these approaches grow rapidly with increasing wind turbine size.

The crucial need for research to improve structural design tools was underscored in recent EPRI work to characterize the rotor wind environment and structural response of a MOD-2 wind turbine. Major additional research efforts are needed to correlate structural field measurements with predictions in an iterative process aimed at developing reliable design tools. These efforts can best be carried out on small and midrange machines, for which the cost of field testing is considerably lower than it is for megawatt-scale wind turbines.

Outlook

The following significant trends in the expanding wind turbine industry will strongly influence the operating experience base over the next several years.

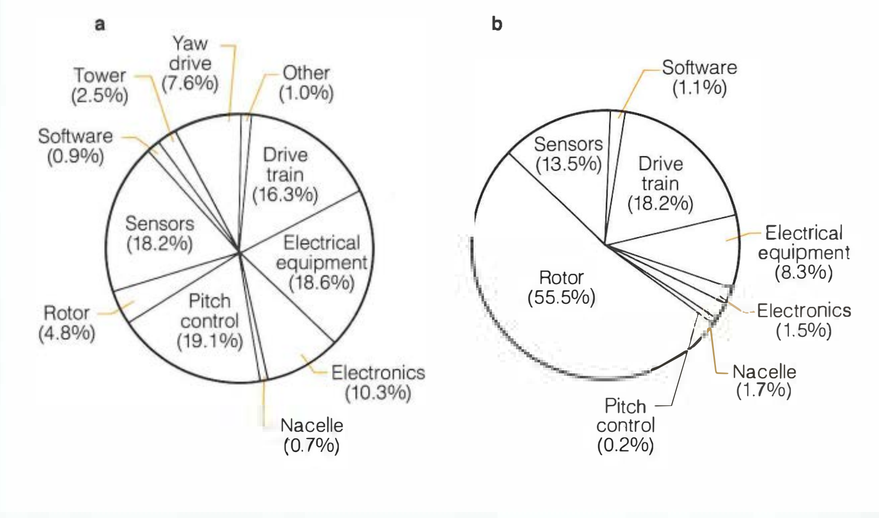


Figure 1 Distribution of unscheduled maintenance manhours by major component for two types of megawatt-scale horizontal-axis wind turbines: (**a**) the 2.5-MW MOD-2 and (**b**) the 4-MW WTS-4. These data are based on EPRI-sponsored field evaluations of five MOD-2 machines and one WTS-4 machine.

□ Wind turbine reliability has become a major issue for developers and investors. Almost all early machines (1981–1982) had serious reliability problems, which resulted in revenue losses (i.e., lower energy production than projected) and high O&M costs. Developers and investors have become more selective and now tend to purchase machines that are showing reasonable reliability growth.

□ To be competitive, wind turbine manufacturers are offering a variety of warranties for their products, including guarantees of annual availability, annual O&M costs, and annual energy production.

□ Wind turbine capital costs have decreased dramatically, from $2000–$3000/kW in 1981 to $1000–$1500 in early 1984. The decrease is attributable to production learning curves, machine simplification, and the trend to larger machines (from 25–50 kW in 1981 to 65–500 kW in 1984). Continued capital cost reduction would support industrial expansion and the growth of the operating experience base.

The trend to midrange machines is significant for a number of reasons. Unlike small turbines, midrange machines seem to have potential for economic viability independent of current tax credits when they become mature products. Also, they could rapidly evolve into utility-grade machines and begin to penetrate the utility market, which is believed to be a principal post-tax-credit market. Thus EPRI is planning significant coverage of emerging midrange machines in RP1996-2 during the next few years.

In work that examined reliability growth in 27 developmental programs involving a variety of technologies, R. Lynette and Associates found that the failure rate of a newly introduced system tends to stabilize after about 20,000 hours of experience. Therefore, depending on the number of wind machines and the strength of the wind regime in which they are deployed, reliability maturation could be expected in three to four years. About the same amount of time is needed to evaluate design trade-offs and determine preferred design approaches for different wind regimes. Hence, given that midrange machines are just beginning to emerge, a mature first generation of fully competitive midrange wind turbines could evolve by the end of this decade. Both horizontal-axis and vertical-axis machines are viable midrange candidates.

In contrast, because of their higher current costs, risks, and complexity, megawatt-scale machines appear to be at least a decade away from being economically attractive enough for major market penetration. If megawatt-scale machines do become a viable technology, they will probably evolve as a generation of scaled-up midrange machines that are less complex than current experimental megawatt-scale machines. This evolutionary growth would parallel that experienced with other technologies. *Project Manager: Frank R. Goodman, Jr.*

RESIDUE GASIFICATION TESTS AT TVA

One of the key technical issues associated with coal liquefaction has been the effective utilization of the unconverted ash-bearing residue. On the basis of process studies performed in the Exxon Donor Solvent (EDS) program (RP778), the Texaco gasification process was identified as an attractive way to use vacuum bottoms, or residue, to generate synthesis gas; this gas can then be upgraded to produce the hydrogen required by the EDS liquefaction process. (Background information on both the Texaco and EDS processes appears in the May 1983 EPRI Journal, *pp. 36–39.) Until recently, the important step of residue gasification had not been demonstrated. To prepare for large-scale testing, the Tennessee Valley Authority (TVA) identified necessary modifications for its 200-t/d gasifier at Muscle Shoals and performed leaching and slurry-handling tests (RP1807). Pilot-scale tests by Texaco, Inc., established operating guidelines (RP714). A $2 million demonstration run, funded by the EDS participants under RP778, was then conducted by TVA.*

Approximately 3700 tons of EDS process vacuum bottoms from Exxon Research and Engineering Co.'s 250-t/d Baytown, Texas, facility were gasified in TVA's ammonia-from-coal facility during 20 on-stream days over a 30-day period with five interruptions. Continuous operation was achieved for periods of nine and six days, each of which ended as a result of instrument problems unrelated to the feedstock or the gasifier. The test program covered a wide range of conditions while achieving a 68% operating factor.

One area that had concerned researchers was the low-melting characteristics of some of the residue agglomerates. Operational changes were made to remove the larger chunks initially and to minimize preheating of the material. An oxygen cooler was added to reduce the potential for deposition in the process burner. Also, a chemical feed tank and an injection pump were installed to provide for the use of a viscosity-reducing additive, which would enable operation at high concentrations of slurry solids.

Before operation with residue, a coal pretest was conducted to confirm operating readiness for the demonstration run and to obtain baseline performance data on the modified system and on an advanced burner designed by Texaco especially for the test to provide performance representative of commercial operation.

Operations evaluation

Researchers found the residue to be easier to mill and less erosive than coal in the grinding operation. However, the wear rates for the type of mill used at TVA were still high relative to rates for typical commercial pulverizers. Thus it was necessary to use the spare mill to facilitate frequent maintenance. During initial operation with residue, the downstream protection systems failed to prevent oversize particles from entering the slurry pumping systems, and two interruptions resulted. Commercial units would use one of several mill types that achieve acceptable wear rates and are equipped with rugged redundant screening systems.

The TVA grinding system, operating at a constant batch rate, produced a particle size distribution similar to that reported for EDS residue at facilities using alternative grinding systems. No attempt was made to study the impact of grinding system turndown.

Because of the lower porosity of the EDS solids, the residue slurry was less viscous than coal slurry even though the residue had a greater proportion of fine particles. As a result, the slurry solids concentration was increased from 65 to 70%. A viscosity-reducing additive was used to maintain pumping performance.

Fourteen separate test periods were completed over a wide range of operating conditions (Table 3). Among the issues addressed were performance at 80% turndown, the minimum operating temperature with good carbon conversion, performance at maximum slurry solids concentration, and performance under steady-state conditions. Because cold oxygen was used, the burner mixing velocity at 80% turndown was equal to that at 60% turndown with a normal oxygen temperature.

Gasification system operation was generally smooth with a few exceptions. During test periods of relatively low carbon conversion, the production of char exceeded the design level and its removal from the system became difficult. These tests were performed at low oxygen consumption, which resulted either from a specified low gasifier temperature or from specified low throughput combined with a high slurry solids concentration (lowest oxygen flow rate). The other problems were related to high particulate carryover in the raw gas and the high solids content of the residue. The carryover caused some gas line plugging and scrubber pump seal failures.

Although the residue contained about twice as much ash as the plant design feedstock (Illinois No. 6 coal), the slag was more concen-

Table 3
OPERATING CONDITIONS FOR TVA RESIDUE GASIFICATION TEST

Operating Condition	Residue Test	Typical Operation With Illinois No. 6 Coal
Gasifier pressure	475–500 psig (3.27 3.45 MPa)	510 psig (3.52 MPa)
Gasifier temperature	2300–2600°F (1260–1430°C)	2500°F (1370°C)
Slurry solids concentration	55–70 wt%	60+ wt%
Slurry feed rate	30–40 gal/min (1.89–2.52 L/s)	
Feedstock rate	150–215 t/d (136–195 Mg/d)	185 t/d (168 Mg/d)
Oxygen feed rate	135,000–180,000 standard ft^3/h (3820–5100 m^3/h)	175,000 standard ft^3/h (4960 m^3/h)
Syngas production (H_2 and CO)	8.1–11.5 million standard ft^3/d (229,000–326,000 m^3/d)	10 million standard ft^3/d (283,000 m^3/d)
Carbon conversion	90–99+%	95–99%

trated than coal slag and the proportion of coarse to fine slag remained relatively high; as a result, there was no significant volumetric increase.

At the high slurry solids concentration attained, it was possible to produce a higher-quality gas (i.e., one with a lower carbon dioxide content) while still achieving the design syngas production rate. The downstream gas-processing systems performed acceptably except for the sour offgas cleanup system, which showed below-specification sulfur removal. This was the result of design problems that were not resolved during previous coal operations. The high ratio of carbon monoxide to carbon dioxide in the syngas at times caused some increased heating of the sour shift catalyst. The Selexol system was able to remove the additional 30% sulfur in the syngas, and through adjustment, the gas's carbon dioxide content was increased to 70% of that typical with coal.

As part of the environmental assessment effort, TVA conducted leachate cell studies (RP1807), which found that storing the residue in open piles in the same manner as coal was acceptable. The existing TVA foam system for dust suppression was used during loading. In other environmental work, Exxon Research and Engineering conducted a comprehensive characterization program for all emissions. In general, Exxon concluded that the process is environmentally acceptable for gasifying EDS residue and that the emissions characteristics are not significantly different from those of coal emissions.

An inspection of the gasification area after the testing revealed a relatively clean system. As in the earlier experience with coal, some deposits were found in the gray water system. A determination of gasifier refractory peak wear and an inspection of the burner indicated that the use of commercial refractory materials and upgraded metallurgy should result in satisfactory service.

The TVA facility was well instrumented for heat and material balance data, with backup measurements in the critical areas. Problems were encountered with on-line gas chromatographs, scrubbed-gas measurement, and soot sampling. Because of the high rate of particulate carryover in the raw gas, adjustments to soot carbon measurements were necessary in order to account for all the carbon in the feed. At TVA the soot is processed as the portion of clarifier fines that passes unsettled from the slag discharge conveyor to a secondary clarifier (ash bin), the underflow of which is discharged separately. The portion of unconverted carbon ending up in the sooty water was higher than that experienced with coal and was imprecisely measured because of difficulties with sampling.

Performance test results

In determining gasifier performance, the atomic oxygen-to-carbon (O/C) ratio is the primary independent variable. The O/C operating range is determined by the gasifier temperature; in general, the upper limit is based on refractory wear, the lower on slag viscosity. At TVA the lower limit was not approached because of the char water clarification design limitations mentioned above. To obtain a characteristic feedstock performance curve relative to the specific burner and grinding equipment, the carbon conversion is plotted as a function of the O/C ratio.

Increases in the oxygen feed produce greater conversion up to a point, beyond which incremental oxygen input produces unwanted carbon dioxide. In general, the lower the O/C value at which the curve flattens, the more reactive the feedstock. Another indication of feed reactivity is whether the slope remains constant at lower O/C or whether it increases (i.e., the curve tails off). Other factors, such as feed temperature, burner characteristics, and grind size, may affect the performance curve.

Understanding these variables is critical to successful scale-up. To gain insight on them, researchers compared the results from the TVA 200-t/d facility with results from similar runs at Texaco's 15-t/d Montebello facility (Figure 2). Both plants used direct-quench-mode gasifiers with Illinois No. 6 residue from bottoms recycle operations.

At TVA, because of the gasifier temperature involved, the test plan called for operating in the lower O/C range for high slurry solids concentrations; because of the low conversion involved, operations were in the higher O/C range for the low slurry concentrations. A comparison of the Montebello and TVA results indicates an apparent scale-up penalty, which Texaco attributes in part to the burner parameters and in part to the greater proportion (5–10%) of coarse particles in the TVA slurry. However, it also appears that there was a significant improvement in performance at TVA with the high slurry concentrations.

The improvement at higher slurry concentrations has not been observed before. Increased concentration results in less water to be vaporized and a higher combustion temperature at a given O/C ratio. Because higher concentrations resulted in higher gasifier temperatures at constant O/C, a kinetic effect seemed feasible. However, low concentrations at low temperatures did not appear to show an equivalent adverse effect on conversion. Texaco attributes the improvement to a decrease in the energy required to vaporize water from the slurry droplet.

The data do not appear to show a significant penalty due to turndown; some effect is evident at the higher slurry concentrations but only when the O/C ratio is relatively low.

Another parameter used to measure performance is the cold gas efficiency, or the percentage of the feedstock's energy that is recovered in the syngas. There was a penalty in the more than tenfold scale-up from Montebello to TVA in that the optimal efficiency at the larger plant was several percentage points lower and was shifted toward a higher O/C ratio. The use of a higher slurry solids concentration at TVA produced improvements in both effects. Efficiency was improved because less energy was required for water vaporization and because less carbon dioxide was pro-

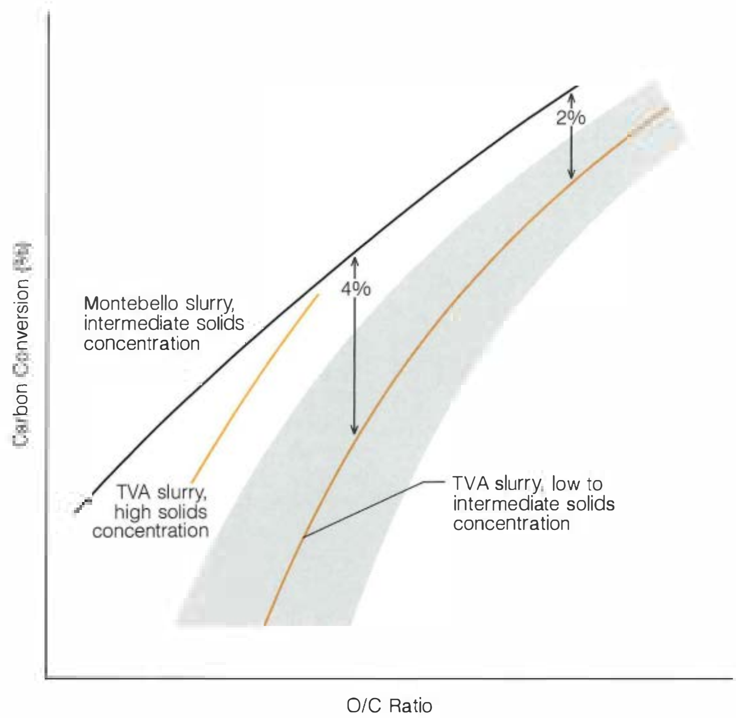


Figure 2 Results from residue gasification tests at the 15-t/d Montebello facility and the 200-t/d TVA plant were compared to study the relationship between carbon conversion and the oxygen-to-carbon (O/C) ratio in scale-up. Increasing the slurry solids concentration at TVA appears to offset the scale-up effect.

duced. The shift toward a lower optimal O/C resulted from the improved carbon conversion. Incremental carbon dioxide production was thereby reduced to half of the 15–20% increase noted in the scale-up.

It appears that the parent coal did not incur the above-noted penalties in scale-up. The residue's incremental performance improvement over coal was substantial at Montebello, whereas the TVA coal pretest data indicate performance similar to that of the residue. Possibly this difference is due to the inability of the 100-ton sample supplied to Montebello to represent precisely the 4000 tons supplied to TVA. Or it could be due to the greater uncertainty in the TVA data. Opposing reactivity effects expected for residuum and refractory unconverted coal, two components of the residue, add to the difficulty of determining the likely explanation. Test results from gasifying a lignite-derived residue at another Texaco facility in Germany, also under the EDS program, may provide additional insight.

The results obtained from this relatively successful scale-up effort provide the know-how needed for additional extrapolation to the 1000-t/d commercial size. Texaco expects that a plant could be designed to handle EDS residue from any high-rank coal, although confirmation tests at Montebello are recommended. In any event, the TVA facility appears to be well suited for the large-scale tests needed to assess the impact of feedstock reactivity on scale-up, to improve equipment design to minimize these effects, and to ensure requisite reliability. *Project Manager: William Weber*

R&D Status Report
COAL COMBUSTION SYSTEMS DIVISION

Kurt Yeager, Vice President

ON-LINE COAL ANALYSIS

Real-time coal analysis gives utilities opportunities for system management previously unavailable. Rapidly determining incoming coal quality, improving blending and cleaning facility performance, and adjusting plant operation are ways in which utilities can use on-line coal analysis. EPRI is leading development of on-line coal analysis technology by contracting the design of prototype instruments and by installing and demonstrating units that meet utility specifications. EPRI has sponsored testing of a sulfur meter at Detroit Edison Co.'s Monroe power station and development demonstration of continuous on-line nuclear analysis of coal (CONAC) at Tennessee Valley Authority's Paradise plant. Tests at these sites show that on-line coal analysis will soon be a valuable technology for utilities.

On-line coal analysis is based on prompt neutron activation analysis (PNAA), a technology that analyzes a moving bed of coal accurately and nondestructively (*EPRI Journal*, June 1981, pp. 32–34). This process offers several benefits. It can analyze large quantities of coal as opposed to the gram-size quantities evaluated in commercial coal testing; the technology is nondestructive and unintrusive; and particle size has little effect on accuracy or precision.

EPRI is developing on-line analysis because monitoring coal properties allows operators better process control, and better and more timely control means saving money. To develop and design a PNAA system specifically for coal analysis application, EPRI contracted with Science Applications, Inc. (SAI), and Kennedy Van Saun, Inc.

Early in the project researchers determined that certain processes were ready for analyzer use, whereas other applications would require some development. For example, monitoring coal inventory, specifically coal blending, was a logical choice for analyzer use because operating a stockpile system is straightforward and avoiding more-costly coal is obviously cost-effective. Thus, when Detroit Edison installed a new coal blending facility at its Monroe plant, the utility also installed an on-line sulfur meter to minimize the use of a higher-cost, low-sulfur coal.

A second ready application for analyzer use is cleaning-plant process control by examining the quality of the cleaned product. TVA's Paradise plant offers such an opportunity; the facility requires clean coal to reduce sulfur content to meet SO_2 emission levels. However, to ensure the power plant's compliance with emission standards, the coal is routinely overcleaned, which causes valuable Btu to be discarded. CONAC installation at Paradise was completed in late 1983 and testing was begun, which continues to the present.

At least two other potential applications are ready and need only an appropriate installation site. The first is monitoring the quality of coal shipments, which would allow users to blend coal feedstocks as they are received and reject substandard coal shipments. The Central Electricity Generating Board (CEGB) of Great Britain is considering this strategy for at least one generating plant. In addition, at least two mining companies are using on-line coal analyzers to monitor the quality of their outgoing shipments. The advantages are obvious for both suppliers and consumers. Suppliers' shipments meet contract specifications, and consumers ensure that they are buying the quality coal they need.

The second application not currently in use is real-time power plant control. By knowing more precisely the quality of its fuel, a utility can control combustion, emissions release, and associated operations more closely. For example, with accurate knowledge of a coal's heat and carbon content, a plant manager can trim excess air without lowering carbon conversion and combustion efficiency. Similarly, by knowing fuel ash content and ash properties, a utility might reduce fouling and slagging incidents. An ideal place for an analyzer in this type of service would be prior to the pulverizer, with the analyzer acting as a combined gravimetric feeder and coal analysis device.

CONAC demonstration

CONAC can measure a coal's constituent elements, moisture content, heating value, ash, and ash chemistry, as well as coal flow through the system. Analysis at Paradise is accomplished by an instrument system with the following components (Figure 1).

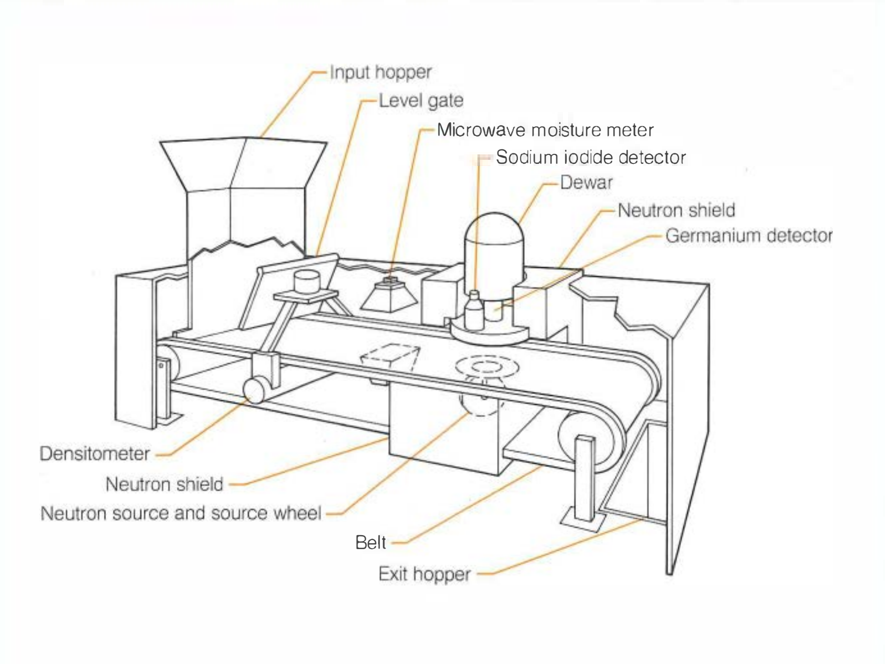
- Two gamma-ray detectors. The first is a high-efficiency, low-resolution sodium iodide detector that rapidly determines coal elements. The second is a high-purity, *n*-type germanium detector with much greater resolution but lower efficiency. This detector ensures CONAC's accurate response.
- An epithermal neutron detector that measures coal hydrogen content.
- A microwave moisture meter that determines coal moisture content.
- A gamma-ray densitometer that measures coal flow through the system.

The Paradise CONAC system (Figure 2) is adjacent to the clean coal sampling tower, which houses a three-stage coal sampling system. Sampled coal is washed at Paradise's 2000-t/h heavy media–flotation cleaning plant. After sampling and analysis, the clean coal is directed either to storage or to the power plant.

EPRI contracted with Bechtel Group, Inc., to design and implement with TVA a test plan that would verify the CONAC system's accuracy and precision and to ensure that CONAC met reliability, operability, and cost standards required by the utility industry.

In this evaluation, accuracy was defined as the bias between the Paradise system's analysis of a particular coal sample and the ASTM laboratory analysis of the same sample. CONAC's precision is the standard deviation

Figure 1 The CONAC system. This cutaway shows the principal instruments and coal-conveying system.



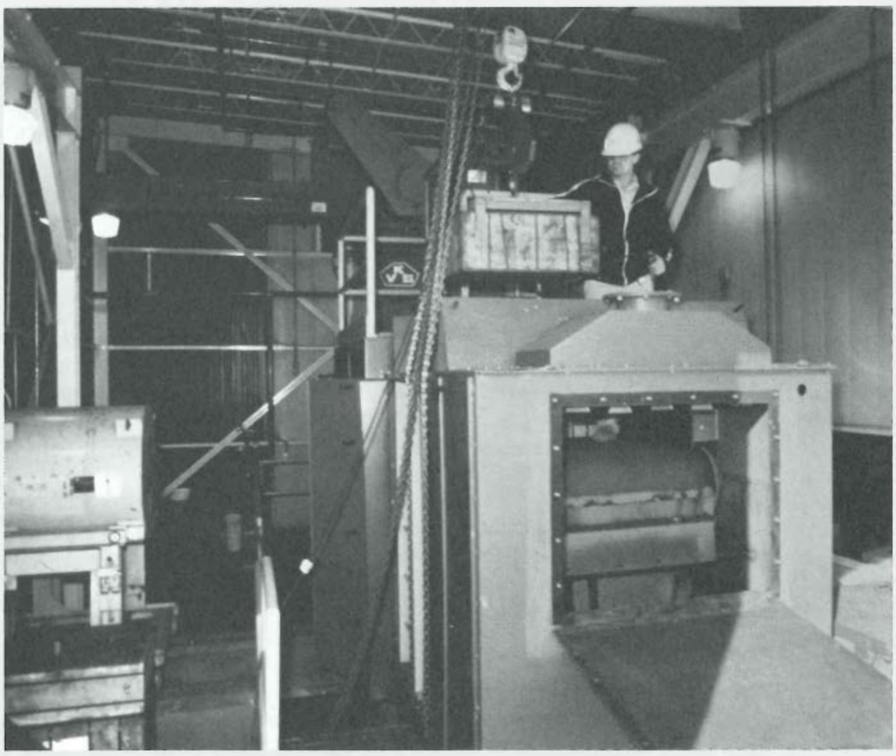


Figure 2 The CONAC system at Paradise. This photograph shows the feed and discharge conveyors, along with the source cask (left) and CONAC control room. The boxed coal sample being lowered into the analysis region is used to calibrate the system.

of a given number of CONAC analyses over a given period. TVA, EPRI, and Bechtel developed accuracy and precision goals by evaluating observed bias between ASTM laboratories, because CONAC should perform at least as well as laboratories adhering to ASTM specifications. Pass/fail criteria were set up to establish a minimum acceptable CONAC performance.

The test plan consists of three phases. The objective of phase 1, the field acceptance test (completed November 1983), was to verify laboratory results at Paradise and to gain operator experience with CONAC. Both objectives were met successfully. In phase 2 (completed in April 1984) project personnel calibrated the CONAC system with boxed samples of TVA regional coals and then tested the system's accuracy and precision by using other coal samples. They used boxed coals for two reasons: boxes enabled careful analysis of small lots by ASTM techniques; the CONAC system's supporting conveyor was not fully operational until mid 1984. Table 1 shows the results of both phase 1 and phase 2 tests. Although nearly all constituents measured met all test goals (except the system's precision test of ash content), system performance improved only moderately after calibration to the TVA region coal set.

Phase 3 is a high count rate test, which began in May 1984 and is still in progress. Before this test phase, CONAC's response was 3 hours for the first output and every 20 minutes thereafter. Although this response is certainly an improvement over typical coal laboratory sample turnaround time (about 36 hours), it is not fast enough for many potential applications. Therefore, SAI enhanced the system with newly developed electronics, which reduces the response time to 5 minutes for a partial analysis and 20 minutes for a complete analysis with ash chemistry. These analyses are integrated by using a special hybrid method that was developed by EPRI in collaboration with TVA. The objective of this phase is to see that CONAC performance still meets accuracy and precision standards with the improved response time and to test CONAC's dynamic characteristics.

Table 2 shows the results of testing boxed coal samples in a laboratory mock-up of the CONAC system. This table shows that all pass/fail criteria were met and that a significant number of goals were exceeded. Noteworthy are the ash and carbon results, which are especially critical and show marked improvement over past efforts.

Dynamic operation of CONAC with loose, bulk coal lots will evaluate a number of variables, including coal throughput (tonnage),

Table 1
CONAC TEST RESULTS (PHASES 1 AND 2)

	Accuracy				Precision			
	Phase 1 RMS Deviation From ASTM (for three coals)	Phase 2 RMS Deviation From ASTM (for five coals)	Pass/Fail Criteria	Long-Term Objective	Phase 1 Standard Deviation	Phase 2 Standard Deviation	Pass/Fail Criteria	Long-Term Objective
Carbon (wt%)	1.80	1.71	5.0	2.0	1.27	1.71	4.0	2.0
Hydrogen (wt%)	0.04	0.08	0.5	0.1	0.02	0.01	0.2	0.1
Ash (wt%)	1.70	0.89	2.0	1.0	1.22	0.55	0.5	0.2
Sulfur (wt%)	0.05	0.15	0.5	0.1	0.06	0.06	0.15	0.05
Chlorine (wt%)	0.006	0.003	0.01	0.005	0.002	0.001	0.003	0.001
Heat content (Btu/lb)[1]	185	189	400	200	139	110	300	200
Heat content (Btu/lb)[2]	196	242	400	200	217	243	300	200
Nitrogen (wt%)	0.16	0.11	0.4	0.4	0.02	0.01	0.30	0.10

[1]Calculated by modified DuLong-Petit method.
[2]Calculated by moisture- and ash-free method.

coal size distribution, moisture content, coal type, and sensitivity to coal bed height and particle segregation. Tests of these properties are currently under way and are scheduled for completion in December 1984. Phase 3 will also assess CONAC's adaptability to alternative coal feedstocks and use strategies.

TVA and Bechtel will prepare a report of the CONAC demonstration, which will discuss all tests and their results and will quantify CONAC's operational characteristics.

Table 2
CONAC TEST RESULTS (PHASE 3)

	Accuracy (for five coals)			Precision (for one coal)[1]		
	RMS Deviation From ASTM	Pass/Fail Criteria	Performance Goal	Standard Deviation	Pass/Fail Criteria	Performance Goal
Carbon (wt%)	0.74	5.0	2.0	1.08	4.0	1.25
Ash (wt%)	0.97	2.0	1.0	0.43	0.5	0.2
Sulfur (wt%)	0.10	0.25	0.10	0.08	0.15	0.05
Chlorine (wt%)	0.008	0.01	0.005	0.001	0.003	0.001
Heat content (Btu/lb)[2]	202	400	175	100	300	100
Heat content (Btu/lb)[3]	242	400	175	70	300	100

Note: Hydrogen and nitrogen were not measured in this phase.
[1]One sigma level.
[2]Calculated by modified DuLong-Petit method.
[3]Calculated by moisture- and ash-free method.

Sulfur meter evaluation

The sulfur meter at Detroit Edison's Monroe plant is a simpler version of CONAC; it uses the same PNAA principles but has only a single sodium iodide gamma-ray detector. A sulfur reading is available every 400 seconds. The meter can handle up to 30 t/h, but because of sampling system limitations, it is only analyzing 3 t/h.

Both Bechtel and Detroit Edison tested the sulfur meter in 1981. The first battery of tests featured a 13-coal calibration, using coals from across the United States. After calibration, researchers analyzed six different coal blends used at Monroe, both on the belt and in boxed samples. Results from the tests were quite good, and the sulfur measurements correlated well with the stack SO_2 monitor readings.

After some delays at Monroe, work with the sulfur meter was resumed in late 1982. Investigators solved a variety of sampling system and sulfur meter problems and recalibrated the system in mid 1983 with 10 boxed coals, representing blends of the 3 feedstock coals now used at Monroe. Overall agreement was ±0.04 wt% sulfur over the range of 0.8–3.4 wt% sulfur. Average precision was ±0.02 wt% sulfur.

These results indicate that the sulfur meter is now a reliably accurate instrument and can be part of a blending strategy. Detroit Edison is developing such a strategy and will publish a report of test results, which should be available in early 1985. Meanwhile, Detroit Edison will continue to test and evaluate its blending strategy and the sulfur meter's role in it.

Future effort

In addition to the two projects discussed above, PNAA-based analysis is being used in at least three other locations in the world. Detroit Edison tests will continue into 1985, quantifying accuracy and operating procedures and outlining economic premises. CONAC high-count dynamic tests will also continue into 1985 to assess the following.

- CONAC response to variations in critical parameters
- Reliability of a sophisticated electronic analyzer in a coal handling plant environment
- CONAC operability
- CONAC operating and maintenance costs

TVA will publish a comprehensive report covering all testing aspects, including an independent assessment of the CONAC system's capabilities. If CONAC performs as well as expected, TVA will integrate it into the Paradise coal-cleaning plant's control system.

Results of this project will greatly help utilities considering coal analysis technology. Future research will study the near-term likelihood of coal analysis for real-time combustion control, which would result in the greatest economic benefits of all.

One unexpected result of on-line coal analysis techniques has been the discovery that laboratories using conventional ASTM sampling and analysis methods do not always achieve expected accuracy and precision. PNAA techniques that analyze greater quantities of coal and hence reduce sampling errors may become the preferred future measurement technique. *Project Manager: Frederick Karlson*

SLAGGING AND FOULING IN UTILITY BOILERS

Slagging and fouling of fire-side heat transfer surfaces of fossil-fuel-fired boilers reduce boiler efficiency, capacity, and availability. Data compiled by the North American Electric Reliability Council (NERC) through the Generating Availability Data System (GADS) show that slagging and fouling cause an average availability loss of 1.6%. In plants larger than 600 MW alone, this loss is estimated to cost the industry over $400 million annually. EPRI is studying the complex mechanisms of slag formation and deposition on boiler heat transfer surfaces in an effort to minimize slagging and fouling problems in both existing and new boilers.

The general objectives of EPRI's research on boiler slagging and fouling (part of a five-year comprehensive program on the effect of fossil fuel quality on plant availability and performance) are to improve technologies for predicting the slagging/fouling potential of any commercial run-of-mine, cleaned, or mixed coals and to improve technologies that prevent, control, monitor, and remove ash and slag deposits from coal- and oil-fired utility boilers. Current projects focus on two areas: (1) understanding how coal characteristics, boiler design, and operating conditions affect slagging and fouling so that researchers can improve prediction techniques, and (2) understanding how fuel additives affect slagging and fouling so that they can be developed and/or effectively used as a viable strategy for dealing with coal- and oil-ash-related problems.

Slagging and fouling prediction techniques

As a first step in understanding why some boilers have serious slagging and/or fouling problems and others do not, EPRI initiated a project to determine if these problems result from coal characteristics, boiler design, or differences in operating or maintenance practices (RP1891-1). This project's short-term objective is to provide utilities with state-of-the-art methods for coping with current slagging and fouling problems on their own equipment. The long-term objective is to be able to predict accurately the slagging/fouling potential of any coal in any furnace.

To accomplish these objectives, EPRI divided the project into five tasks.

- Survey utility field experience
- Survey boiler manufacturer design methods and prediction techniques
- Analyze coal characteristics, boiler designs, and operating conditions and their relative importance to slagging and fouling
- Review indexes used by manufacturers to determine the extent of and reasons for limited index applicability
- Produce two topical reports and one final report

Topical reports will describe utility experience in minimizing slagging and fouling problems and the effects of furnace design factors on slagging and fouling. The final report will summarize project findings and discuss deficiencies in present slagging/fouling prediction techniques for future research.

In one analysis, the contractor, Battelle, Columbus Laboratories, used only the coal-slagging factor (base/acid × sulfur), for example, and compared the prediction with actual field experience (Table 3). Assuming that the predicted slagging categories of low, medium, high/severe correspond to rare, occasional, and frequent slagging occurrences, respectively, the slagging factor produces about 50% correct predictions. Comparison of one coal classification and one boiler design parameter analysis with slagging frequency for boilers that fire coal having a bituminous-type ash ($Fe_2O_3 > CaO + MgO$) gives the curve in Figure 3, which correctly classifies 90% of the boilers by their actual slagging frequency.

The study indicates that predicting coal slagging potential can be much more accurate when slag indexes based on coal parameters are used with boiler design parameters. Investigators are also analyzing subbituminous and lignite coals. This project is scheduled for completion by December 1984.

Fuel additives

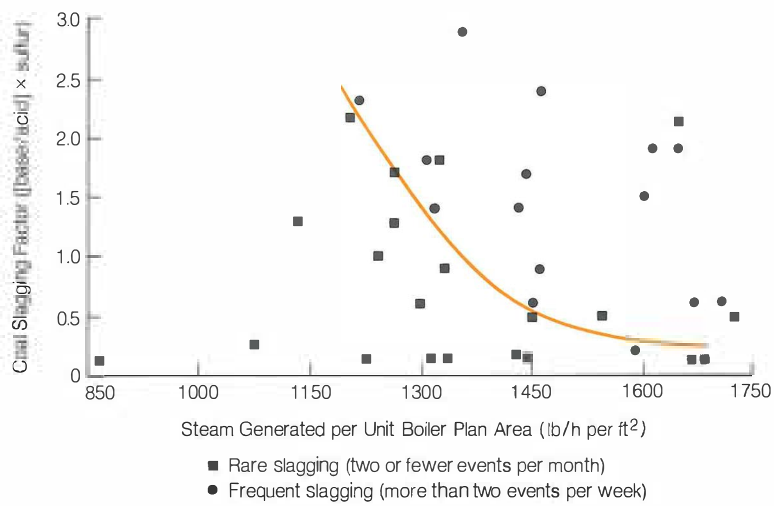
Recent work documented utility use of combustion fuel additives to correct common problems that relate to coal ash and oil ash (CS-1318). Researchers concluded that use of fuel additives is a viable strategy for solving certain oil combustion–related problems (i.e., fouling, fire-side corrosion, stack opacity) and that fuel additives may also solve similar coal-related problems. They also concluded that the results of using the same additive in different plants were not uniform and that additive action was not clearly understood. As a result, EPRI has begun four additional projects to learn more about additive action and to advise utilities on additive use.

One of these projects guides utility selection of additives containing magnesium and manganese for reducing high-temperature fouling and corrosion in oil-fired boilers (EPRI CS-

Table 3
COMPARISON OF PREDICTED SLAGGING AND FIELD EXPERIENCE

Reference Values		Field Experience		
Slagging Factor	Slagging Potential	Rare	Occasional	Frequent
<0.6	Low	12	6	2
0.6–2.0	Medium	7	12	10
>2.0	High/Severe	2	4	3

Figure 3 Slagging experience related to slagging factor and combustion intensity. This presentation of slagging experience for dry bottom units fired with bituminous coals shows that both coal properties and boiler design are important in determining whether or not a unit slags.



3281). The contractor used a small-scale combustor to produce gases and particulate solids from residual fuel oil under conditions similar to those in a utility boiler; air-cooled tubes in the gas stream simulated superheater tube surfaces. Investigators used commercial additives and compared additive concentration, excess air, and particle size. They compared treated and untreated fuel oil for deposit composition and adherence, tube metal corrosion, and SO_3 reduction. The results indicate that magnesium and manganese additives substantially reduce deposit adherence. Fine-particle magnesia is best for corrosion reduction; manganese is less effective. Operation with low excess air reduces SO_3 as effectively as additives at high excess air levels. Reducing magnesium oxide particle size permits lower dosage rates.

A second project, which was more exploratory in nature, investigated, identified, and evaluated the effects of additives on coal ash sintering strength (EPRI CS-3270S). Project personnel sintered cylindrical pellets of coal ash from three utility sites, each of which uses a different eastern coal and each has a slagging problem. They then measured the compressive strength of each sintered pellet and repeated the process, introducing different additives (silica, calcium, magnesia, and dolomite) into the pellets before sintering. The additives were mixed as dry powders with the coal ash particles of 2-, 10-, and 50-μm diam at a concentration of 1% of the coal ash by weight.

Project results show that fuel additives can significantly reduce the sintering strength of some types of coal ash deposits. Mixing small amounts of additives into the fly ash reduced ash sintering strength. Magnesia was the most effective, followed by silica, but the results depended on the type of coal ash used and the atmosphere in which the sintering took place. Simulated furnace gas, containing realistic SO_2, H_2O vapor, Na, and CO_2 levels, is more conducive to sintering than is air. Evidence indicated that transport of species vapor from the coal ash and modification of additive particle surfaces that absorb the species may be the mechanism that accounts for the initial formation of interparticle bonds rather than the bulk composition of the ash itself.

In pilot-scale combustion tests, a third project is demonstrating volatile additives' potential as a cost-effective solution to some U.S. coal ash slagging/fouling problems (RP1839-4). In the United Kingdom, France, and Finland, one additive, copper oxychloride, was used in small quantities (g/t) and demonstrated that some slag characteristics could be changed so that the slag can be easily removed by conventional ash removal systems. The mechanism for this remarkable effect on certain coals is not understood at the present time.

The methodology in this third project will be to (1) gather data from the European experience with copper oxychloride (i.e., coals used and the analysis of field and laboratory tests), (2) select a known slagging U.S. coal of similar characteristics for pilot-scale combustion tests, (3) test the selected coal with and without the additive, and (4) analyze slag samples from treated and untreated coals to determine the mechanism involved.

Investigators will then study additive effects on the basis of the extent and nature of the deposits/slag buildup in the pilot-scale combustion facility; document and determine follow-on work for copper oxychloride field demonstration; and test other additives with similar or superior properties on the pilot scale. The project team expects to complete this work by December 1985.

A fourth project on combustion fuel additives is developing a manual on fuel additives for utility use in combating common types of problems related to coal ash and oil ash (RP1839-3). This manual will advise plant operating personnel on additive selection, feeding systems, testing procedures and equipment, and the evaluation and reporting of additive performance. This project will be completed in December 1984.

As U. S. utilities turn to coal as their primary fuel and deplete quality resources, they will be forced to burn poorer quality coals, which promote slagging and fouling problems. Recognizing the serious financial effects slagging and fouling can have on power plant operation, EPRI is working to provide utilities with alternative strategies (i.e., coal cleaning, fuel additives, water blowers, and prediction methods) for dealing with slagging and fouling problems. *Project Managers: Arun K. Mehta and Barry Dooley*

R&D Status Report
ELECTRICAL SYSTEMS DIVISION

John J. Dougherty, Vice President

TRANSMISSION SUBSTATIONS

Insulation coordination of HVDC converter stations

A significant interest in HVDC systems has developed in the past few years. This interest stems from a need either to transmit a large block of power over significant distances or to tie a weak system into a power grid through a back-to-back converter system. A project has been initiated with General Electric Co. to develop a handbook that will explain how the insulation coordination is carried out by using gapless metal oxide surge arresters for HVDC converter stations (RP2323-1).

The basis for insulation coordination and the selection of characteristics for equipment in an HVDC converter system should be such that the equipment will not be damaged by any overvoltage generated during normal or abnormal system operating conditions. As in all engineering activities, the system must not only function properly and reliably but also be designed so it can be constructed economically. In the HVDC converter system, the surge arrester selection and location process has a major effect on system reliability, component equipment characteristics, and cost of a converter terminal. The development of the modern zinc oxide arresters has allowed a significant design advantage over the conventional dc arrester.

Additionally, several unique applications using zinc oxide arresters have been suggested. These applications have to be explored, and if found to offer advantages, they will be folded into the present insulation coordination methods. Their overall effect on system operation, reliability, and cost must also be examined.

Overvoltages encountered in an HVDC converter station can be caused in a variety of ways—for example, by uneven distribution of voltages across individual thyristors during blocking, turn-on, and turn-off periods, which can overstress some of the thyristors; commutation overshoots; voltages across inductors by di/dt surges; control contingencies producing abnormal operating sequences and consequent overvoltages; startup or blocking procedures or commutation failures that can also cause overvoltages. These are some of the peculiarities of the converter stations that the insulation coordination study must address above and beyond the normal switching, lightning, and ferroresonance-caused overvoltages experienced in the ac systems. Because it is undesirable to interrupt power flow for certain predictable overvoltages, the basic insulation level must accommodate such contingencies.

Also, if the power flow is interrupted and overvoltages result from surplus reactive power, ferroresonance, and so on, it should be possible to suppress/damp these overvoltages for a sufficient period of time to switch the reactive power sources in or out, allowing restart of the power flow.

Very fast surges can occur for faults between the converter transformers and smoothing reactor; these can stress the converter insulation because of uneven voltage distribution during the critical period of valve recovery, when a valve may not be protected by its arresters.

Certain events may result in high overvoltages across the equipment (rather than to ground), such as a smoothing reactor, the neutral terminal of wye-connected valve winding, or a 6-pulse bridge in a 12-pulse converter.

Energy capability of arresters is a very important parameter, and parallel columns may be needed to handle the necessary energy, which, in turn, may lead to derating of energy capability per column.

Clearly, equipment costs can be minimized by establishing minimum insulation levels, as well as enhancing system performance by coordinated action of arresters, switching, and converter control and protective actions.

Because the overvoltage surges may have a whole range of rise times (not just the standard impulse and switching surges), the impedance-frequency characteristics of equipment may be important in computations of surges getting through the transformers, reactors, or capacitors.

This study is intended to result in a handbook, generic in nature, for a more economical specification of HVDC substations by utilities in the future. The format will enable utility personnel to use it without resorting to proprietary computer programs or simulation methods. The project should be completed by mid 1985. *Project Manager: Vasu H. Tahiliani*

HVDC circuit breakers

The September 1983 *EPRI Journal* (pp. 46–47) described the development and testing of two promising dc breakers for full-scale field testing (RP1507). Bonneville Power Administration (BPA) conducted field tests February 26–27, 1984. The Los Angeles Department of Water & Power and Southern California Edison Co. also cooperated in this project. These were the first successful full-scale field tests on complete HVDC breakers.

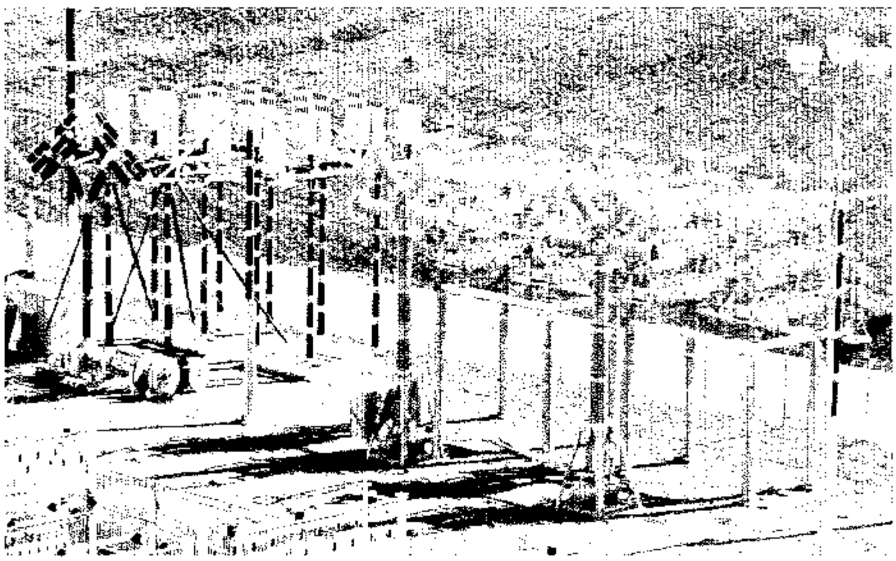
The HVDC breakers were installed at BPA's Celilo station at The Dalles, Oregon (Figure 1). The terminals and the 846-mi-long (1356-km) line that constitute the HVDC Pacific Intertie were used for the tests, which were conducted at 400 kV dc with currents up to 2000 A.

The Brown Boveri Corp. (BBC) breaker was an air-blast type with a permanently connected L–C commutation circuit, which successfully switched fault currents up to 2000 A.

The Westinghouse breaker was of the SF_6 puffer type and used a switched capacitor for the commutation circuit. Its maximum short-circuit ability was limited to 1200–1400 A primarily because of mechanical difficulties with the switch that was used to insert the commutating capacitor. Time did not allow for correcting the mechanical difficulty, and tests were limited to a maximum of 1200 A.

The short-circuit tests were conducted with faults applied at the Celilo terminal, at a point approximately 250 mi (400 km) from Celilo (at

Figure 1 Dc circuit breakers under test at Bonneville Power Administration's Celilo terminal in February of this year. The Brown Boveri unit is on the left; the Westinghouse unit is on the right.



the Sylmar terminal). In addition to the fault tests, line switching, loop breaking, and three terminal tests were conducted on both breakers. All these tests were successful.

Currently under consideration is a proposal to increase the BBC breaker's interrupting capability to 4000 A and decrease its fault-clearing time from approximately 60 ms to 30 ms. For the longer term, additional work is being evaluated to implement the SF_6 puffer technology for this application.

The significance to utilities of the success of this project is that operation of long-distance, multiterminal HVDC lines or networks is now possible. The breaker configurations tested were constructed of relatively standard off-the-shelf components, such as ac breaker poles, capacitors, and zinc oxide surge suppressors. The devices are also of modular construction, which contributes to versatility in application. In addition, the use of relatively standard components should ensure their commercial viability. *Project Manager: Joseph Porter*

POWER SYSTEM PLANNING AND OPERATIONS

Fast stability analysis

A major activity in power system planning and operations is the simulation of disturbances to test for network stability. The results of these simulations are used to choose needed electrical equipment and set operating limits. A very fast and inexpensive method of performing these important studies has long been desired. Such a method, called direct stability analysis, was successfully tested on small (17-generator) networks (RP1355-3).

The speed and low cost of a direct stability analysis capability will yield immediate dollar savings (if stability is a limiting factor) by permitting increased economic energy transfer between companies or more-efficient power plant use. Specifically, a first-swing stability analysis tool that runs as fast as a comparable load flow has many applications in on-line dynamic security monitoring, in operations planning, and as a screening tool in expansion planning.

Ontario Hydro is building on the success achieved in RP1355-3 by expanding the method to accommodate large, realistic networks; making the software easier to use; and testing the software extensively to ascertain its speed and reliability (RP2206). Thus far, the researchers have calculated the stability of a 17-generator network (classic model) in about 0.2 s on a VAX computer, which is roughly 10 times faster than with traditional methods. Tests have been successful on networks of up to 100 generators, although some computation problems have arisen when analyzing large, highly stressed networks. Experience shows that the analysis time required increases as the square of the number of generators.

The software and method development will be completed in early 1985. Extensive testing will then be performed by using four different test cases. In addition to EPRI-funded projects, Ontario Hydro is currently adapting the method for the real-time control of a 3600-MW nuclear generating station. Test results and prototype software will be available in late 1985. *Project Manager: James V. Mitsche*

Optimal power flow research

Optimal operation of a power system implies minimum cost of operation; at the same time, security, reliability, and constraints on equipment operation must also be considered. Because of the size and complexity of today's power systems, computer programs help system dispatchers and planning engineers arrive at optimal operating conditions. Not only real power flow but also reactive power flow and bus voltages must be scheduled if the power system is to be operated as efficiently as possible. And now, rising fuel costs, questionable fuel supplies, decreasing system reserves, and limited operating budgets have created conditions that must be simulated more accurately for proper resolution.

The intent of the first phase of this research on optimal power flow is to develop a set of recommendations for large-scale, optimization-type computer programs (RP1724). An industry survey provided application and user requirements, and a literature search determined the best solutions for each application. Utility interviews supplemented the questionnaire and literature search. The larger issues to be addressed were the potential applications and the solution procedures. This first phase identified both planning and operation requirements (including real time) for the optimal power flow. A workshop will be held during the first quarter of 1985. A handbook on optimization for power system planning and operations will be published during 1985. Energy Systems Computer Applications, Inc., is the contractor for the first phase of the project.

During the second phase, a production-grade solution module will be developed for use in several EPRI programs and for distribution by the Electric Power Software Center. This module should be completed by the end of the first quarter of 1986. *Project Manager: John Lamont*

Data transfer and conversion

As power systems have grown and higher voltage interconnections have been made, the need to exchange power flow and stability data for planning and operations has increased severalfold.

Data transfer between areas is complicated by noncompatible model formats in the different computer programs used to model the same problem. Such different models result from valid but different applications of engineering principles.

As the amount of data to be converted from one format to another increased, utilities developed additional computer programs to automate data conversion. Over the last two decades, three specific formats evolved and became widely recognized as major exchange formats for power flow and stability data: the IEEE common format (widely used in the eastern United States), the Western Systems Coordinating Council (WSCC) format (widely used in the western United States), and the Philadelphia Electric Co. (Peco) format (used by utilities and power pools utilizing the computer programs that were developed by Peco and the Pennsylvania-Jersey-Maryland Interconnection).

Boeing Computer Services, Inc., has completed a set of three short-term translators that will convert both power flow and stability data. The first converts either IEEE or Peco power flow data into WSCC format. The second converts EPRI's power flow history file to IEEE format. The third converts either IEEE or Peco stability data to WSCC format. The first two have undergone utility testing and are available from the Electric Power Software Center. The third is currently being tested and will be available by the end of 1984. *Project Manager: John Lamont*

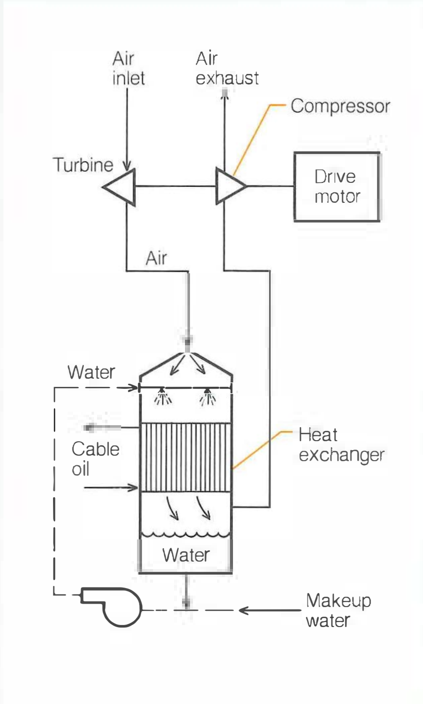
UNDERGROUND TRANSMISSION

Air-cycle cooling for HPOF cables

One of the alternatives to increasing the ampacity of a high-pressure oil-filled (HPOF) pipe-type cable is to circulate the oil and cool it externally. Several methods in various combinations are currently used to provide the external cooling, such as oil-to-air heat exchangers (precoolers), oil-to-water heat exchangers, or mechanical refrigeration with a vapor-compression cycle.

Because this cooling equipment is large and both its first cost and its maintenance costs are high, there exists considerable room for improvement. The relatively low duty cycle of existing units also suggests the need for compact portable equipment that can be used as a peaking unit in emergency situations. In 1978 EPRI funded the development of equipment that uses air as the cooling medium, but in a more compact arrangement than conventional precoolers (RP7866). A prototype unit, nominally rated at 158 kW (45 t), was manufactured and sent to EPRI's Waltz Mill Cable Test Facility for further evaluation, with tests directed toward establishing the range of performance of the system, its operating characteristics, and its endurance capability.

Figure 2 In the basic air cycle proposed for cooling oil in HPOF cables, additional capacity is achieved because the air temperature drops 35°C as it passes through a turbine at the inlet and because water sprayed on the airstream evaporates on the heat exchanger surfaces.



The basic air cycle, specifically the subatmospheric reverse Brayton cycle, is shown in Figure 2. A compressor and turbine operate on a single high-speed (32,000 rpm) shaft. The compressor creates a partial vacuum in the heat exchanger compartment and interconnecting piping so that the incoming air works on the turbine as it enters the system. In the process, the air temperature drops from 35° to 0°C, greatly improving the cooling effect of the air on the heat exchanger. Additional capacity is achieved by spraying water into the airstream and evaporating it on the heat exchanger surfaces. The following equipment was manufactured as a prototype for this project.

- The turbine-compressor unit with its drive motor and gearing
- A compact oil-to-air heat exchanger
- Interconnecting piping, including a water trap for minimizing the quantity of entrained water carried into the compressor

Four independent variables have a significant effect on the cooling capability of the air-cycle system: oil inlet temperature, spray water flow rate, oil flow rate, and the air temperature entering the heat exchanger. A series of 90-min steady-state tests were run over a range of these independent variables. The most significant test result shows that (as expected) the addition of spray water rapidly increases the cooling capacity of the system. However, when the spray water flow rate reaches about 95 mL/s (1.5 gal/min) the cooling rate levels off, with higher water flow providing little additional cooling. Other results showed a rapid increase in cooling rate as the inlet oil temperature increased and a more moderate increase as the oil flow rate increased.

To achieve the design conditions of 58°C inlet oil temperature, 25°C outlet oil temperature, and 2.52 L/s (40 gal/min) oil flow rate, a cooling capacity of 141 kW is required with Sun-4 oil. The capacities demonstrated in the tests performed at Waltz Mill are 117 kW with a spray water flow rate of 158 mL/s (2.5 gal/min) and 113 kW with a spray water flow rate of 95 mL/s (1.5 gal/min). These values are 17–20% below the design capacity for wet operation. For operation without spray water, dry operation, the measured cooling capacity exceeded the design value by 9% (34.5 versus 31.6 kW).

Air-cycle cooling has both advantages and disadvantages when compared with conventional refrigeration. Among the advantages are (1) the air cycle can be made more compact than a conventional refrigeration system; (2) although the noise level of the air cycle is quite high, the fact that the noise is concentrated in the higher frequencies makes it easy to attenuate; and (3) cold weather startup of the air cycle unit is more easily accomplished.

Among the disadvantages are (1) power consumption of the air cycle unit can be double that of a conventional unit, and (2) the air-cycle system requires the use of small quantities of water to achieve reasonable capacities.

The final report for this project is available (EL-2130), and the subject was thoroughly covered at the 1984 IEEE Summer Power Conference, paper No. 84-SM 500-5, by Burghardt and Cooper of Westinghouse Electric Corp. *Project Manager: John Shimshock*

R&D Status Report
ENERGY ANALYSIS AND ENVIRONMENT DIVISION

René Malès, Vice President

PCB EXPOSURE ASSESSMENT

Polychlorinated biphenyls (PCBs) are a family of chemical compounds, usually in an oily-looking liquid form, that are well known for their stability, excellent dielectric and cooling properties, and resistance to fire. PCBs exist in more than 200 possible chemical structures, although only a very few of them are actually produced and used. Because of their properties, PCBs have been widely used in many types of electrical equipment, including large and small capacitors, fluorescent lights, motors, and appliances. Capacitors and transformers contain most of the PCBs, although the chemicals have also been used in hydraulic heat transfer systems, pigment manufacture, rubber and resin plasticizers, carbonless copy paper, dedusting agents, and adhesives. Concern about possible health effects has resulted in increasingly stringent regulations governing PCB use. EPRI research is developing models for determining the fate of these chemicals once released to the environment.

Two events in the late 1960s first caused concern about PCBs. One was the discovery of PCBs in a number of environmental samples tested for DDT and chlorinated hydrocarbons. The other was the outbreak of health problems after rice oil was accidentally mixed with PCB oil in Yusho, Japan. Subsequent discoveries of contamination in the Great Lakes and the Hudson River and animal laboratory studies linking PCBs with possible health effects prompted Congress to authorize the Environmental Protection Agency (EPA) to promulgate regulatory measures. The vehicle for this authorization was the 1976 Toxic Substances Control Act (TSCA). In 1979 EPA issued regulations that banned PCB manufacture, processing, distribution, and use except in completely enclosed systems, such as capacitors and transformers. These regulations defined mixtures containing PCB concentrations of 50 parts per million (ppm) or greater as PCB-contaminated and 500 ppm or greater as PCBs. These new regulations spurred the utility industry to improve methods for cleaning up PCBs spilled from ruptured or leaking equipment, to develop methods for identifying equipment likely to fail, and to accelerate replacement of PCBs and PCB-contaminated equipment. Late in 1979 the Environmental Defense Fund challenged the new regulations in court, particularly EPA's choice of 50 ppm as the base for contamination. The court ordered the agency to initiate new rules.

The utility industry, led by the Edison Electric Institute and the Utility Solid Waste Action Group, negotiated with EPA to survey utility equipment and devise an interim measures program to inspect and maintain utility equipment. The survey produced the most comprehensive inventory to date on the numbers and types of PCB-filled equipment, PCB levels in the equipment, the frequency of failure and associated release rates, related health effects, and important environmental transport pathways. According to the survey, utility electrical equipment contained 163 million pounds (74 million kg) of PCBs, most of which were contained in capacitors purchased before 1977. The rest were found in transformers containing askarel, a mixture of PCBs and chlorinated benzenes. A small amount of PCBs were also found in about 10% of those transformers containing mineral oil. (It should also be noted that at a number of locations the PCB-filled transformers are owned by customers, not by utilities.)

PCB release

Capacitors and transformers release PCBs when they leak or rupture, spilling the compounds over the immediate area. The size of the release depends on the type of failure and the type and size of the equipment.

Release frequency depends on a number of factors, such as periodic inspections. Inspections have reduced capacitor rupture rates from 10% in 1970 to 1% in 1980. Transformer failure rates have always been much lower.

Release location varies by unit type. Capacitors are used throughout the distribution system, in substations, in generating facilities, and in transmission systems, as are mineral oil transformers. Askarel transformers are more commonly found in locations where fire safety is of importance, such as in substations, generating facilities, or buildings. Thus, release to the environment can occur in almost any location.

PCB migration, fate, and effects

PCB migration on land surfaces and in aquatic systems is largely controlled by the movement of sediments and other particulates because of PCBs' affinity for adsorption. This mechanism controls the rate at which PCBs will leach through soils and move into groundwater systems, particularly if soil clay content is high. The quantities of PCBs that can be transported in fluid are also limited because PCBs do not dissolve readily in water. Although PCBs can migrate in the atmosphere, airborne quantities are limited by their moderate volatilization rate.

These descriptions of PCB migration are general. Specific behavior of individual forms depends on the degree of chlorination. Less-chlorinated PCBs tend to be more mobile than more-chlorinated forms.

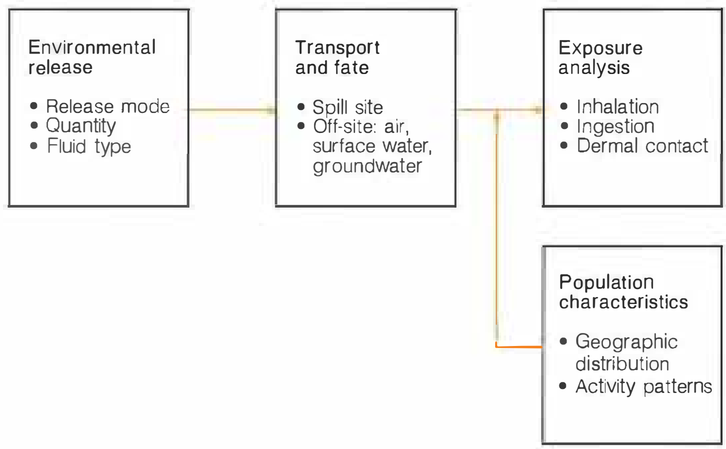
PCB fate is largely controlled by photolytic degradation, biodegradation, deep burial by sediments, and bioconcentration/biomagnification. Photolytic degradation is not actually a fate mechanism but does result in the dechlorination of PCB compounds. As a result, the dechlorinated compounds are more biodegradable.

As the debate on PCB cleanup has intensified, the utility industry's need to predict PCB levels in soil, air, and water after a spill has grown. Utilities must decide which strategy to pursue for PCB cleanup. Extensive PCB sampling in various media would make the choice of strategy easier; however, sampling is extremely expensive. An alternative is to develop a methodology that can be used to predict the environmental concentrations and associated exposure levels. EPRI is developing just such a methodology.

Exposure assessment methodology

Figure 1 shows the components of the PCB-spill exposure assessment methodology. Various factors, among them release mode and fluid quantity and type, govern environmental release. After release, a number of processes act to transport the PCB in air, water, and soil. The transport and fate component of the methodology contains several models, a spill-site model and some off-site models. The spill-site model is a modification of a tested EPA chemical transport model, PRZM (the pesticide root zone model). The off-site models are established air, surface water, and groundwater models; these are based on closed form solutions to differential equations, whereas the more-complicated PRZM model uses a numerical solution technique.

Figure 1 The key components of the PCB spill exposure assessment methodology are environmental release, transport and fate, population characteristics, and exposure analysis. Shown with each component are the major factors that have to be considered.



Once a PCB spill occurs, a number of key hydrologic and transport processes come into play, depending on whether the spill is on soil or asphalt/concrete. From soil, PCB may volatilize and enter the atmosphere, leach through soil into groundwater, or drain into surface water. If it spills on concrete, the compound may volatilize and/or drain into surface water.

The off-site models are a Gaussian plume dispersion model, an analytic surface water model, and a simple analytic groundwater model. These models predict PCB fate as the compounds volatilize into the air, drain into surface water, or leak into groundwater.

Exposure can occur by three routes: inhalation, ingestion, and dermal contact. Population distribution and activity patterns determine contact. The exposure model includes a general exposure analysis framework for estimating exposure levels for each route. This framework is currently used by EPA.

The exposure model is the first step in evaluating the risks to humans or ecosystems from PCBs. Such an evaluation should help utility decision makers assess alternative strategies for handling equipment containing various amounts of PCBs. Evaluations with this model show the probability of actual human exposure to be relatively low, and if a population is exposed to PCBs, the PCB concentration is likely to be very small. Such information is the basis for policy decisions and must be evaluated in terms of both the costs to prevent exposure and the value society puts on such prevention.

Utilities will soon test the exposure assessment model, which will be useful to the industry and government policymakers responsible for establishing PCB cleanup standards. *Project Manager: Abraham Silvers*

UTILITY INVESTMENT ALLOCATION METHODS

The electric utility industry is one of the most capital-intensive industries in the United States. In recent years the industry's business environment has become more uncertain. Utilities have reacted by attempting to identify alternative investment opportunities that are less capital intensive than traditional supply alternatives and that can be implemented in small increments. These alternatives decrease the amount of capital required; nontraditional investments allow greater flexibility in the investment commitment process. To take advantage of the new alternatives, utilities have to understand their effect on the company's financial performance. EPRI is sponsoring research in utility investment allocation methods to develop ways of evaluating capital investment alternatives from a strategic and financial management point of view. Initial research indicates that existing computer models, with some modification, appear adequate to support utility strategic investment allocation decisions, and no new models have been developed. However, the analysis necessary for the comprehensive evaluation of alternative investment opportunities is new, and its integration into traditional utility planning is complex.

Traditional utility planning focused on choosing conventional power plants on the basis of conventional decision criteria, such as revenue requirements and service reliability. Today, utilities have a variety of options that fall into the broad categories of supply, end use, and new businesses (Figure 2). The problem lies in determining how these options contribute to customer service requirements and how much return and risk they represent to the company.

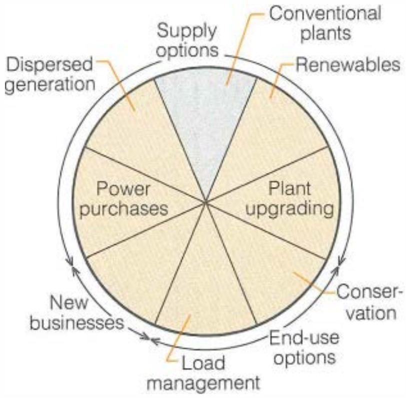
Capital rationing assumes that the amount of investment funds is limited and that increasing the amount of investment in one option decreases the amount available for others. A company must decide, for example, whether a megawatt of load management is equivalent in cost and risk to a megawatt of wind power or what mix of options will allow the company to earn its cost of capital with acceptable risk.

Traditional analysis, using an annual fixed-charge rate, does not help in this type of decision making. Utilities need more advanced engineering-economic techniques that can distinguish between different investment risks and evaluate the options simultaneously. The literature on these techniques is still developing and a convincing, operational method for analyzing the allocation problem for any industry has yet to be identified. EPRI has undertaken several projects to develop methods utilities can use to allocate investment capital.

Plant life extension

The objective of this research (RP2074) is to provide utilities with a method for analyzing in-

Figure 2 Utility capital investment alternatives. The gray portion shows traditional utility planning. Today, utilities can use a number of alternative investments (color) to reduce capital requirements.



vestments in plant life extensions, availability improvements, and upratings. The cost of upgrading a unit is generally treated by most utilities as a capital expenditure. In this project researchers evaluated alternative investments by using the present value of associated incremental revenue requirements. They calculated additional measures of investment worth, such as the internal rate of return, benefit-cost ratio, and discounted payback, and compared these measures with revenue requirements. They also developed three hypothetical case studies of increasing complexity. In addition to analyzing a single rotor replacement investment, investigators simulated a life extension program for 12 coal cycling units (about 30% of the case study utility's capacity). A major part of this program was estimated to be completed in about 10 years at a cost of $427 million (1983 $). Figure 3 shows the incremental revenue requirements: a net $684 million decrease in the present value of revenue requirements, with fuel as well as capital savings contributing to this outcome. A significant part of the savings, however, accrues after 1995, and the amount of the savings is uncertain.The discounted payback period is approximately 10 years; thereafter, the program is self-supporting. Savings for the first plants contribute to paying for succeeding plants. Also, extending plant life requires relatively little capital and short lead times.

However, a number of uncertainties not tested in this study could affect the return on this investment. Because utilities have little experience operating life-extended plants, actual plant performance and the duration of the proposed extended lifetimes are unknown. In addition, extending the lives of certain plants at this time may necessitate complying with pending environmental regulations. Therefore, although the upgrading investment seems attractive, it has some risks that are not well understood. Project personnel identified these risks and calculated their effect on program cash flows.

Modeling and valuation

In this project researchers used a utility strategic planning model to simulate a range of investment strategies: (1) conventional baseload capacity expansion, (2) plant life extension, (3) smaller plants with short lead times, (4) peak load shifting, and (5) a 10-year moratorium on all new capacity (RP2379-6). The model showed financial accounting results, revenue requirements, net cash flows, dividends per share, and electricity price trajectories. Project personnel analyzed the investments from three points of view: utility management, using net cash flows; utility investors, using dividends-per-share growth rates; and customers, using electricity prices.

Not unexpectedly, investigators found that the three measures of investment worth often, but not always, resulted in different investment rankings and that these rankings depended on the time over which the investment was evaluated. The project team also analyzed the reasons for the differences. The project report ranks the investment strategies in terms of their present value, at various discount rates, of net cash flows, dividends, and consumer prices (EA-3531). Eight different future business environments were evaluated to test the sensitivity of the investment to key uncertainties.

Although much work has yet to be done in the area of utility investment valuation, the preliminary results presented in the report are an important and original contribution to understanding disparate utility investments.

Investment risk

Much of the work described in this status report concentrated on the risky cash flows in nominal dollars associated with a particular investment. Choosing a discount rate to convert these risky cash flows into a present value is also difficult—and controversial.

The objective of a scoping study reported in EA-3214 is to describe the methods utility managers should consider when selecting individual investment discount rates. The starting point, or benchmark, for the methods, which

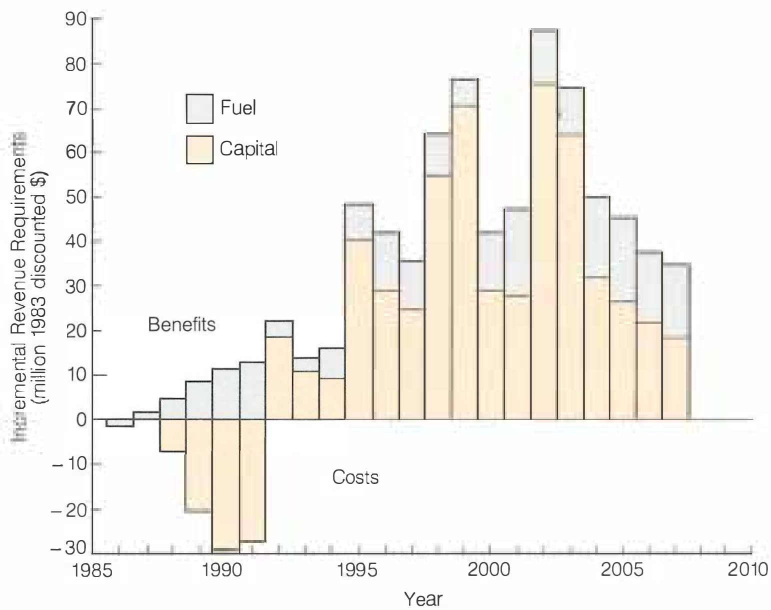


Figure 3 Hypothetical case study. Upgrading substantially reduces revenue requirements by both saving fuel costs and postponing new capacity. The present value of saving in revenue requirements for this investment amounted to $684 million.

are based on the principles of corporate finance, is the capital market, where required returns (in this context, synonymous with discount rate) on financial instruments increase with their perceived risk. The study divided the markets into three broad risk classes by major industry category and, on the basis of historical data, estimated the required returns by industry risk class (Table 1).

The study suggests that managers compare the incremental net cash flows associated with a particular investment directly with capital markets data to infer an appropriate discount rate. Three approaches are suggested for different situations.

- The investment corresponds to a well-defined line of business in which there are comparable companies whose securities are traded in capital markets: Use capital markets data on business risk with the market risk-return relationship to infer the appropriate discount rate.
- The investment corresponds to a well-defined line of business, and the expected cash flows are reasonably similar to those of some other operating companies, but there are not enough comparable companies whose securities are traded: Develop data on the accounting variability of the line of business; compare this measure of accounting risk with capital markets measures of business risk to estimate the investment's business risk; then use the market risk-return relationship to infer the discount rate.
- The investment as a whole is fundamentally different from operating companies: Attempt to divide the investment into distinct cash flow streams that have comparables; then use market risk-return relationships to infer separate discount rates for as many pieces of the investment as possible.

Table 1
REQUIRED RETURNS

Industry Class	Required Returns (%, adjusted for inflation)
Low-risk	4–6
Medium-risk	6–10
High-risk	10–15

Current EPRI research on choices of discount rates for risky investments (1) compares and contrasts decision analyses and corporate finance approaches to investment valuation, and (2) analyzes appropriate rates to discount revenue requirements.

Risk analysis

EPRI recently initiated a new project in this area (RP2442). Its objective is to document the sources of risk that affect different utility investments and to develop a consistent, practical analytic approach that provides usable measures of risk to the utility decision-making process. This project will produce several reports: a briefing report that categorizes and defines utility investment risks, a report on currently used methods to analyze and communicate investment risk, and case study reports on the application of risk analysis approaches in a number of utility situations.

EPRI is also publishing a bimonthly newsletter, "Utility Investments Risk Analysis," in connection with this project. The newsletter provides a forum for discussing utility risk-related issues and an outlet for preliminary and interim results from the research project itself.

Future research

EPRI is continuing work on investment evaluation and choice in two areas: risk analysis (RP2442) and the cost of capital/discount rate (RP1920, RP2379). The next step will be in the area of risk management options. The objective of this research is to identify generic risk management opportunities corresponding to different utility investment alternatives. This work will use information from the ongoing projects described above and from related EPRI research on plant modularity, new technology risks, and fuel management.

Another planned research project focuses on supporting the investment decision process within the utility organization. It will develop a practical decision support system consisting of analytic tools, integrated management information systems, and information communication frameworks. This system will differ from conventional management information systems (which are mostly used for routine operating decisions) in its focus on relatively unstructured and often unique investment allocation decisions. *Project Manager: Dominic Geraghty*

R&D Status Report
NUCLEAR POWER DIVISION

John J. Taylor, Vice President

CORRELATIONS IN RADIONUCLIDES IN LOW-LEVEL WASTES

Provisions of 10 CFR, Part 61 (Licensing Requirements for Land Disposal of Radioactive Waste), together with amendments to 10 CFR, Part 20 (Standards for Protection Against Radiation), describe licensing procedures, performance objectives, and technical criteria for licensing waste disposal facilities. These regulations require nuclear plant operators to quantify the concentrations of several radionuclides in nuclear wastes. Foremost among them are the isotopes tritium, nickel 63, and strontium-90 and the long-lived isotopes carbon-14, technitium-99, iodine-129, and certain transuranics. In many cases measurement of these radionuclides requires highly specialized analytic techniques, and the majority of these isotopes go undetected in routine analysis because of their extremely low concentrations and their beta decay mode. To help utilities quantify these radionuclides, EPRI initiated a project to study the correlations between them and the more easily identified isotopes (RP1557-6). Establishing such correlations would allow waste generators to quantify these difficult-to-measure nuclides.

Correlation methodology

Developing correlations between waste radionuclides requires a fundamental understanding of the process by which radioactive material is transported from the core to the reactor coolant and finally to the waste streams. Two distinct processes produce radionuclides: fission and neutron activation. The fission-product nuclides introduced into the reactor coolant are related to the fuel performance. The activation products depend primarily on construction materials and the behavior of corrosion products in the circulating reactor water.

The composition of the waste activity will depend on the nuclide production rate and transport mechanism. Concentrations of radionuclides that are physically and chemically similar should correlate. Similar nuclides released to the coolant by the same method should also show a strong correlation. For example, an earlier EPRI transuranic study found a correlation between plutonium-239, plutonium-240, and cerium-144 (RP613). These nuclides are all fuel-related isotopes released directly from the fuel to the reactor coolant. In addition, these nuclides have similar chemical characteristics; they are generally insoluble in liquid systems. All are long-lived isotopes that would undergo little decay in the transport process. The expected correlation between these isotopes in the final waste materials is verified by plant measurements.

The methodology involved scaling difficult-to-measure nuclides to those more easily measured, such as cobalt-60 or cesium-137. Both are normally present in measurable quantities in nuclear wastes.

The correlation between cobalt-60 and nickel-63 best explains the methodology. Nickel-63 is formed by the neutron activation of elemental nickel. The primary source of this material is stainless steel components in BWRs and Inconel tubing in PWRs. Cobalt-60 correlates with nickel-63 because it is also an activation product from the same materials and should exhibit similar chemical and physical properties. Both cobalt-60 and nickel-63 should be released from the fuel by similar thermal and hydraulic mechanisms. Once released to the reactor coolant, they may be removed in waste and purification processes in the same proportion because they are both insoluble.

The isotopes of principal concern have the following properties.

□ Tritium is produced in the reactor fuel either by nuclear fission or by neutron activation. It has a 12.3-year half-life by emitting a very low energy beta particle (0.0186 MeV).

□ Carbon-14 is produced by neutron activation of nitrogen-14. This isotope decays with a 5730-year half-life by emitting a beta particle with an energy of 0.156 MeV.

□ Technitium-99 is produced in the decay process of the fission product molybdenum-99. This nuclide has an extremely long half-life, 212,000 years. The beta emission produced in the decay has an energy of 0.292 MeV.

□ Nickel-63 is produced through the activation of elemental nickel present in steel and high-nickel alloys. It, too, decays by emitting a low-energy beta particle (0.067 MeV) with a half-life of 92 years.

□ Iodine-129 is produced in the decay of the fission product tellurium-129. The principal emission is a beta particle of 0.150 MeV. This isotope has an extremely long half-life of approximately 15 million years.

□ Several nuclides of concern fall into the general classification of transuranics. All those of interest in waste disposal have fairly long half-lives and decay by alpha emission.

Waste streams

Except for the gaseous activities and tritium, essentially all radionuclides released from the reactor system either decay at the reactor site or are discharged through the radwaste system as ion exchange resins, filter sludge, concentrated liquids, or trash and scrap material.

Researchers took samples from four nuclear plants during this study: two BWRs and two PWRs. Sample points and procedures were established for each participating plant, tailored to its system configuration and waste generation experience. Investigators paid particular attention to the sampling process to ensure, to the extent possible, representative samples. However, representative sampling proved to be difficult. To offset this problem, project personnel took a series of samples and selected the sample for detailed analysis on the basis of preliminary plant testing. Averaging the results over the study period also served to further reduce concern over sample effects.

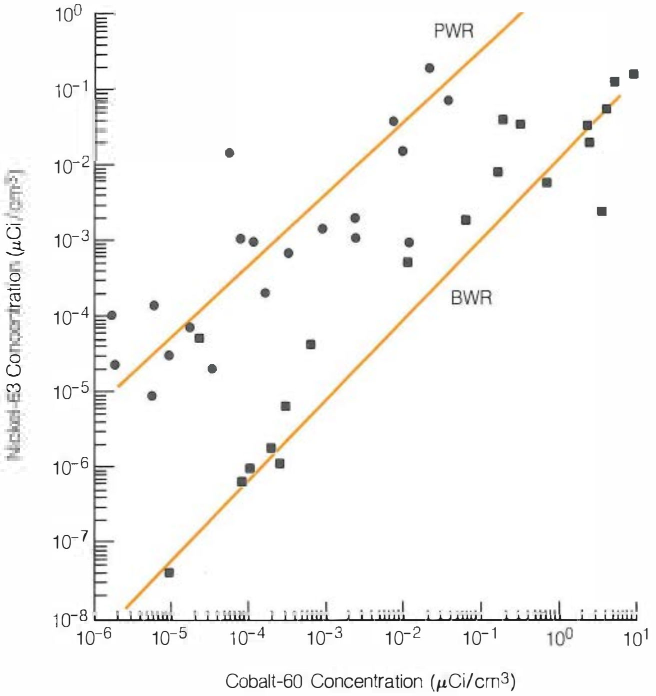
To aid in establishing a data base of sufficient size, researchers asked the utilities operating nuclear power plants to contribute their analytic results to the study. This contribution increased the number of samples from approximately 40 to over 700, which improved the statistics of developing correlations between the waste radionuclides.

Correlation results

Figure 1 shows the results of the sample analysis. Note that the ratio of nickel-63 to cobalt-60 does not vary significantly. A slight variation may result from small differences in the quantities of parent metals present in the respective reactor systems. The correlation for each reactor type is excellent and should prove to be a generic correlation for waste measurements. Utilities can use this correlation to estimate the amount of nickel-63 by measuring the amount of cobalt-60. The correlation allows utilities to meet the requirements of 10 CFR, Part 61 without bearing the cost and delay of highly sophisticated analytic techniques.

The correlation of cobalt-60 to nickel-63 is one of a number of such relationships currently being studied. However, it is unlikely that many of the correlations will be generic to all plants. Some correlations may require plant data for calibration to a specific plant's waste. Researchers are confident that several correlations will allow their use in estimating waste nuclide concentrations. *Project Manager: Michael D. Naughton*

Figure 1 The nickel-63 and cobalt-60 activity found in waste samples taken from BWRs and PWRs is shown in this graph. Each point represents the concentration found in one specific sample. Note that the results of both the PWRs (circles) and the BWRs (squares) are closely grouped along common lines. These lines define the correlating relationship found between these nuclides in the study.



DYNAMIC EFFECTS OF PIPE RUPTURE

Nuclear reactor systems and components important to safety must be protected against the postulated effects of pipe whip and discharging fluids that may result from pipe ruptures. In the absence of quantified information and more-refined analytic procedures, conservative assumptions for pipe rupture opening time and area to nature of impact are applied in the various steps of design and evaluation. These assumptions have resulted in designs with massive devices, such as pipe whip restraints, that are expensive and inconvenient, particularly for maintenance and operation. This status report describes EPRI-sponsored experimental and analytic efforts to develop more-realistic criteria and methods for improving current design and evaluation.

Appendix A to 10 CFR, Part 50 requires that systems and components important to safety "be appropriately protected against dynamic effects, including the effects of pipe whip and discharging fluid (jet impingement), that may result from postulated piping ruptures." Reactor designers and operators can provide this protection in many ways, from initially designed separation to avoid direct impact to retrofit devices, such as pipe whip restraints. The assumptions used in evaluating pipe whip and jet impingement greatly influence the type of measures taken. A typical current-generation PWR can have 250–400 pipe whip restraints, which can cost an estimated $20–$40 million per unit to design, procure, and construct. This cost estimate does not include additional operating costs associated with in-service inspection and maintenance that result from difficult access and other design problems. Even more important, the difficult access increases occupational radiation doses for maintenance personnel.

The size and number of protective devices are a direct result of the assumptions and procedures used in design. Generally, industry practice has been to use conservative engineering judgment and logic for ensuring upper-bound considerations. To improve current practice, the industry needs criteria and methods based on mechanistic assessment of actual pipe rupture phenomena and their effects, including studies of pipe whip impact, jet impingement, and pipe rupture and depressurization. EPRI has sponsored both analytic and experimental research in these areas to meet the nuclear industry's needs.

Pipe whip impact

In the first phase of a study on pipe whip impact (RP1324) researchers reviewed the state of the art to identify general research needs. EPRI report NP-1320 documents the general design survey and discusses research needs in pipe rupture–related areas, such as pipe whip impact, jet impingement, and pipe rupture opening time. The second report, NP-1208, concentrates specifically on analytic assessment of pipe whip and identifies needed nonlinear modeling features and reliable numerical schemes. After completing the survey, project personnel began the experimental investigation and analytic code development. The entire pipe whip study is scheduled for completion by the end of 1984.

France's Commissariat à l'Energie Atomique (CEA) and Framatome (with major funding from EPRI) have joined EPRI in the experi-

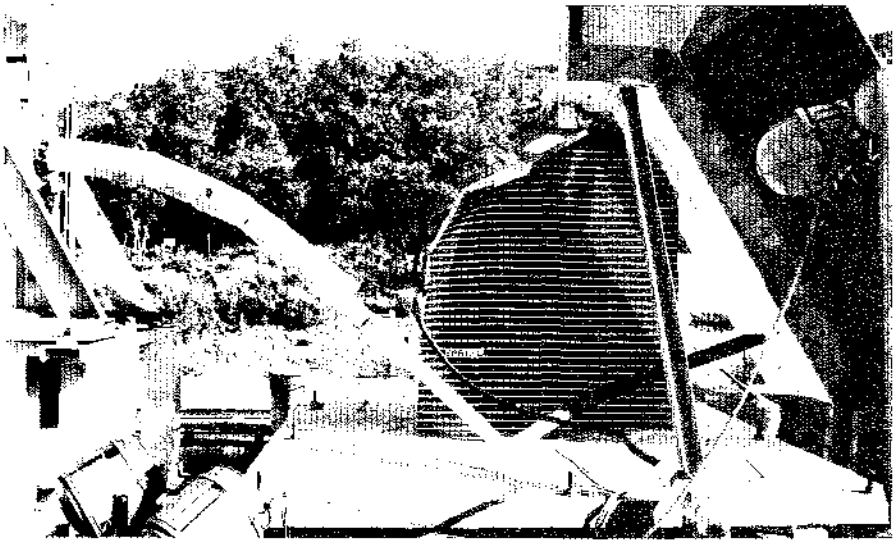


Figure 2 Pipe impact on a concrete slab 4.5 in (114 mm) thick in pipe whip studies. This test induced a slight dent in the concrete at the impact region. The total impact force measured at the concrete supports was 101,200 lb (46 Mg).

mental effort at CEA's Cadarache Laboratory. Researchers completed 16 tests with 3-in schedule 80 (or 10) carbon steel pipes hitting a rigid target or concrete slab. Figure 2 shows pipe whip impact on a concrete slab. The major testing parameters include distance from original position to point of impact, impact location, pipe rupture location, and concrete slab thickness and strength. The most important finding is pipe crushing at impact and the interaction between the pipe and the slab. Depending on the slab strength and thickness, the pipe may penetrate the slab or induce hairline cracks in the back face only. These tests do not represent any prototypical design configuration. The main objective was to generate a data base for validating the highly nonlinear methodology required for realistic pipe whip impact analysis. A secondary objective was to quantify the conservatism in current simplified industry practice in analyzing pipe whip problems.

EPRI also sponsored the development of a more-advanced method for pipe whip analysis. This work resulted in a finite-element computer code, ABAQUS–ND, for general nonlinear dynamic analysis of pipe systems, including pipe whip. Additional development and joint sponsorship with other organizations have expanded ABAQUS–ND to include very general nonlinear capability for structural analysis.

The expanded version, called ABAQUS–EPGEN, has been used to analyze selected CEA tests, including the effects of large deformation and strain rate on resisting moment and energy absorption at the impact region. The results show that pipe crushing has to be considered in the impact region to account for energy absorption and obtain meaningful results. Researchers also studied the simplified approach described in American National Standards Institute (ANSI) 58.2 recommended by the American Nuclear Society. Comparison of measured impact loads to ABAQUS–EPGEN and ANSI results show that ABAQUS– EPGEN results agree well with measurements on the upper-bound but that the simplified ANSI approach predicts loads three to four times the measured ones.

Jet impingement

For jet impingement studies, EPRI cosponsored the Marviken full-scale jet impingement test program with Canada, Finland, Italy, Japan, The Netherlands, Sweden, and the U.S. Nuclear Regulatory Commission (RP1733). The principal objective of this project was to provide large-scale experimental data on the behavior of two-phase jets as they exhaust from the choked pipe into the containment. These data, together with data from small-scale experiments, provide the information necessary to develop and verify analytic or empirical models used to estimate jet impingement loads in nuclear plant safety analysis.

The test program studied both jets with a free expansion and jets directed toward instrumented targets. The free expansion tests showed the axial and radial pressure distribution in the jet for different flow regimes; the jet impingement tests measured the total target force and the force distribution on targets in the jet stream. Twelve tests simulated breaks of various diameters with mixed flow regimes of various phases, from subcooled water through pure steam.

Test data show that highly subcooled jets expand rapidly beyond the nozzle exit plane, resulting in substantially smaller pressures and impingement loads than those predicted by current ANSI methods at target distances greater than one nozzle diameter. Subcooled water jets with a target-distance-to-nozzle-diameter ratio of approximate unity had measured loads slightly larger than predicted. The measured loads for steam jets were comparable to the values predicted by the ANSI method. Investigators analyzed the jet impingement test data by using the more sophisticated K–FIX computer code and found good agreement.

EPRI also sponsored a simplified but more-realistic two-phase jet study, using the method of characteristics solution technique. Model predictions of jet centerline static pressure compare well with data for jets with steam and two-phase stagnation conditions. However, predictions of jet behavior for jets with subcooled stagnation conditions in the region near the jet discharge are more difficult, and the model tends to overpredict jet centerline pressures.

Pipe rupture and depressurization

The design acceptance requirement, which assumes an instantaneous guillotine pipe break, has resulted in very conservative pipe restraint systems and pipe whip barrier designs. In an EPRI-sponsored study researchers concluded that dynamic crack propagation is controlled by inertia and a finite time is required to completely sever the pipe (NP-2440). The highly ductile nature of pipe material prevents pipe cracks from propagating instantaneously.

Consequently, the industry needs quantitative results backed by experimental data to define more-realistic initial depressurization conditions in pipe whip design. Recognizing this need, EPRI sponsored a test program of high-energy pipe leak and break experiments (RP2176). Personnel conducted the first six tests on 6-in stainless steel and carbon steel pipes under either PWR or BWR fluid conditions. The pipes tested had axial cracks with initial machined-in surface flaws. The range of machined flaws encompassed important combinations for studying both subcritical crack leak conditions and supercritical crack unstable rupture conditions.

Because of the extremely difficult problem of controlling crack initiation and fluid condition at temperature and pressure and the high-energy environment associated with large steam leakage, no good crack propagation data were obtained. However, investigators did get significant qualitative data. They found that pipe rupture will occur only if the pipe wall contains a sufficiently long unstable part-through crack in which is embedded a long unstable through-wall crack. All other flaw configurations will result only in a pipe leak. Figure 3 shows a pipe crack opening of a subcritical stable crack configuration.

For the full rupture cases induced by unstable cracks, the measured values of the reaction force are smaller by a factor of approximately two than those calculated by using the ANSI design formula for pipe rupture cases. Although the tests are of axial crack configurations, the results have strong ramifications for circumferential cracks, as well as for pipe whip reaction force. The limited number of tests does not provide enough data to evaluate pipe rupture opening time. However, the data do show that the simplified method for evaluating pipe rupture–induced reaction force is conservation, and the pipe will leak before break because the possibility of an undetected unstable through-wall flaw embedded in a long unstable part-through flaw is low.

Current industry view

The ductile nature of pipe material makes pipe rupture unlikely. Plant operation experience provides sufficient evidence to substantiate this industry view. In fact, the stringent requirements on Class I pipe system design virtually eliminates the possibility of pipe breaks. German licensing has moved toward removing pipe whip and jet impingement considerations in the primary system. An NRC-sponsored study at Lawrence Livermore National Laboratory may also recommend discarding guillotine-type pipe break assumptions in the design of PWR primary systems and removing the requirement of pipe whip restraints and other mitigative requirements. On behalf of the industry the Atomic Industrial Forum is coordinating additional recommendations on more-generic criteria that include other pipe system classes.

EPRI's pipe whip and jet impingement research provides important data and methods for more-realistic evaluation of pipe rupture dynamic effects in cases in which pipe rupture remains postulated. However, because the probability of pipe rupture is low, EPRI's future research will emphasize leak-before-break, as well as quantify crack propagation and leakage under operating LWR fluid conditions. *Project Managers: H. T. Tang, R. B. Duffey, and A. Singh*

Figure 3 The shape of an opening crack in postulated pipe rupture studies. This test had an unstable through-wall crack initiated in a subcritical partial through-wall crack. The total leakage area was 5.6 in^2 (36 cm^2).

New Contracts

Number	Title	Duration	Funding ($000)	Contractor / EPRI Project Manager
Advanced Power Systems				
RP1654-25	Effects of Carbon Dioxide on Low-Rank Coal Grindability in Slurry Preparation	4 months	73.9	Brookhaven National Laboratory *G. Quentin*
RP2526-2	Characterization of KILnGAS Waste Waters	3 months	60.0	Oak Ridge National Laboratory *M. Epstein*
RP2544-1	High-Efficiency Axial Compressor	9 months	173.0	General Motors Corp. *A. Cohn*
RP2562-3	Expert System Evaluation	1 year	50.0	Arinc Research Corp. *C. Dohner*
RP2564-90	NO_x Reduction in Small Gas Turbine Power Plants	2 years	118.5	Gas Research Institute *L. Angello*
RP2565-4	Technical Support for PSE&G Repowering Project	7 months	44.8	Mark Waters & Associates, Inc. *H. Schreiber*
RP2656-1	Utah Coal Test With the Mining and Industrial Fuel Gas Program	3 months	84.3	Black, Sivalls and Bryson, Inc. *M. Epstein*
RP2620-2	Survey of Alternative Gas Turbine Engine and Cycle Designs	8 months	39.9	Encotech, Inc. *A. Cohn*
RP2659-1	Utah Coal Test Run on TVA's Texaco Gasification Process	6 months	1284.0	Tennessee Valley Authority *G. Quentin*
Coal Combustion Systems				
RP1184-11	MMS Validation: Simulating Low-Load Operation in Fossil Fuel Plants	4 months	51.0	Science Applications, Inc. *F. Wong*
RP1184-12	MMS Interactive and Color Graphic Fossil Fuel Plant Analyzer	3 months	31.9	Systems Control, Inc. *F. Wong*
RP1863-2	Evaluation of Acoustic Boiler Leak Detection Methods	16 months	140.1	Battelle, Columbus Laboratories *J. Scheibel*
RP2113-5	Cooling-Tower Performance Test Facility: Data Analysis	28 months	95.4	Tennessee Valley Authority *J. Bartz*
RP2253-7	Remaining-Life Estimation of Boiler Pressure Parts: Creep Crack Growth Studies	16 months	161.0	Westinghouse Electric Corp. *R. Viswanathan*
RP2369-51	Analysis of Historical Low-Sulfur Coal Market	4 months	50.0	Resource Dynamic Corp. *J. Platt, R. Row*
RP2481-2	Evaluation of Temper Embrittlement in Low-Pressure Rotors	28 months	695.3	General Electric Co. *R. Viswanathan*
Electrical Systems				
RP1280-91	Development of a Direct Embedment Foundation Design Procedure	13 months	64.0	Jersey Central Power & Light Co. *V. Longo*
RP1529-4	Computational Enhancements: Large Deviation Approximation to Generating-System Reliability Evaluation	1 year	30.0	University of Pittsburgh *M. Pereira*
RP2028-12	State-of-the-Art Review: PCB Substitutes and Their Pyrolysis/Combustion Products	5 months	56.6	SCS Engineers *G. Addis*
RP2239-2	Linemen's Protective Equipment: Phase 2	13 months	220.0	Battelle, Columbus Laboratories *R. Tackaberry*
RP2358-2	Advanced Tree Trimming Equipment: Engine-Powered Climb Crew Tools and Rope Thrower Systems	17 months	235.0	Engineered Systems & Development Corp. *H. Ng*
RP2542-1	Characteristics of Lightning Surges on Distribution Lines	47 months	1668.5	Power Technologies, Inc. *H. Songster*
RP2589-1	Distribution Transformer With Electrohydrodynamic Pump	11 months	92.0	General Electric Co. *J. Porter*
Energy Analysis and Environment				
RP1826-17	Noncarcinogen Risk Estimation	7 months	68.6	Science Research Systems, Inc. *P. Ricci*
RP2343-1	Response to Innovative Rate Structure	23 months	260.4	Laurits R. Christensen Associates, Inc. *J. Chamberlin*
RP2369-52	Coal Quality and Cost Production	4 months	56.0	TERA Corp. *J. Platt, M. Miller*

Number	Title	Duration	Funding ($000)	Contractor / EPRI Project Manager
Energy Management and Utilization				
RP1041-20	Assessment of a Centralized Medium-Size Fuel Cell Power Plant	7 months	146.7	Kinetics Technology International, Inc. *E. Gillis*
RP2220-1	Hybrid High–Coefficient of Performance Heat Pump: Market Study	7 months	128.6	Mechanical Technology, Inc. *A. Karp*
RP2285-8	R&D Planning Assistance for the Buildings, Lighting, and Refrigeration Subprogram	5 months	48.7	W. I. Whiddon & Associates *G. Purcell*
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EPRI Project Manager: W. Weber

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