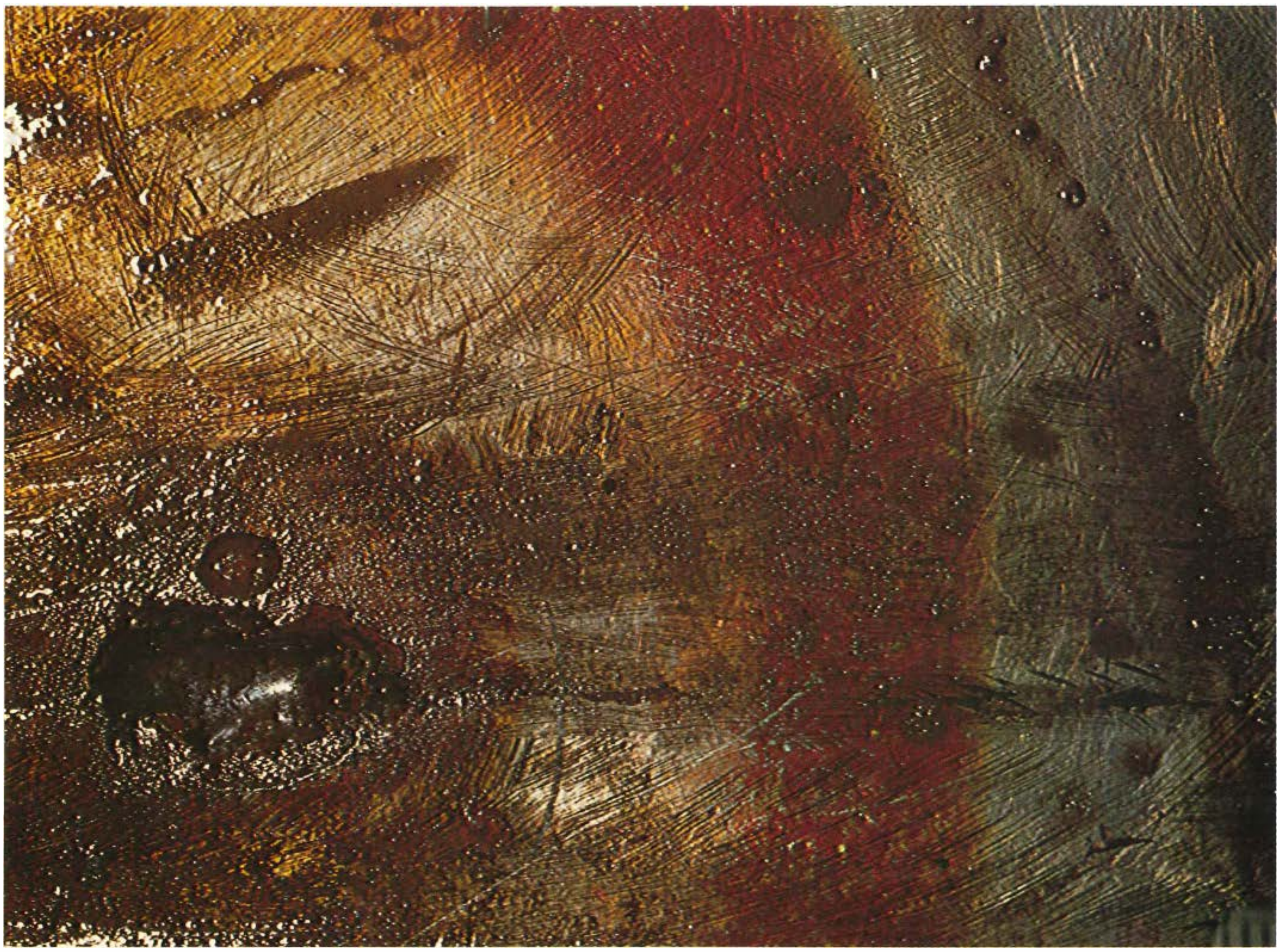
Corrosion

ELECTRIC POWER RESEARCH INSTITUTE

EPRI JOURNAL

SEPTEMBER 1981



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

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

Address correspondence to:
Editor
EPRI JOURNAL
Electric Power Research Institute
P.O. Box 10412
Palo Alto, California 94303

Cover: Deep pitting of this welded seam is evidence of the corrosion that can attack wherever hot gases, water, and steam flow in a power plant. *Photo courtesy Pacific Gas and Electric Co.*

EPRI JOURNAL

Volume 6, Number 7 September 1981

Corrosion Management

EPRI is acutely aware of the importance of corrosion to the reliability of utility equipment and devotes at least 10% of its R&D budget to the measurement, control, and alleviation of corrosion. An important part of the EPRI corrosion management program is communication with utilities on how to understand corrosion issues and how best to approach the corrosion problem. Materials are of primary concern here, and care must be taken to go beyond first-cost considerations in planning an economic system—an inadequately corrosion-resistant material selected on the basis of a low first cost may lead to excessive forced outage and high replacement power costs. For example, the use of carbon steel instead of chromium stainless steel for the tube support plates of PWR steam generators proved to be false economy because the growth of magnetite in the crevice between the tube and tube support plate was much greater than general corrosion rates would indicate and contributed to an expensive denting problem. In another example, recent Japanese and European experience suggests that an all-titanium welded condenser, which is much more expensive than a copper-tubed condenser cooled by salt or brackish water, may pay for itself in the long run, particularly in terms of the reliability of the plant as a whole.

Plant operation is probably the most important concern in a utility's corrosion management program. The turbine and steam generator manufacturers have established extremely stringent standards for steam purity. To operate a steam power plant within these limits requires extensive instrumentation. Constant vigilance is the watchword in maintaining steam purity, and the operator must use his authority to shut the plant down when the limits are exceeded.

Design is also important. Occasional upsets in plant operating conditions are inevitable, and the design of the system must be able to cope with such upsets. Often this amounts to taking into account the corrosion-degraded performance of the material when designing the component. The more-rugged designs that result can offer a useful alternative to the use of more corrosion-resistant materials. For example, in the presence of corrosive deposits from condensing steam, the type-403 chromium stainless steel used extensively as a steam turbine blade material undergoes extensive pitting and may lose much of its fatigue strength. The blade designer may choose to base specifications on the reduced corrosion fatigue strength of pitted type-403 or to select a nonpitting grade of stainless or titanium alloy as the blade material.

Corrosion could be an even greater threat to utility equipment than it is but for the conservatism of the design codes. However, the codes address the situation only in terms of general corrosion and do not specifically recognize stress corrosion and other localized problems. Thus EPRI's extensive efforts that target these localized corrosion types in applied research are quite important. However approached, whether through improved materials, operational controls, or corrosion-cognizant designs, corrosion management is essential for reliable utility operation.

Robert I. Jaffee

Robert I. Jaffee
Technical Manager
Materials Support

Authors and Articles

Technology always imposes trade-offs. The vacuum created in a steam condenser markedly boosts the efficiency of the turbines in a power plant. That same vacuum sucks at every turbine shaft seal and every tiny leak in the condenser tubes. The ingress of airborne oxygen and waterborne minerals at these points can mean corrosive attack wherever the feedwater and steam flow.

In **Corrosion** (page 6) Feature Editor Ralph Whitaker travels the circuit of a steam electric power plant to review some of the causes, effects, and remedies that R&D is identifying for various types of corrosion. The technical guides are two EPRI metallurgists, Adrian Roberts and Barry Syrett.

Roberts joined the Nuclear Power Division in September 1974 after six years in the materials science division of Argonne National Laboratory, where he was first an investigator of nuclear fuel properties and ultimately a supervisor of research in fuel and other materials for fast reactors. Roberts managed EPRI research projects in core materials until 1979, when he spent a year at Cornell University as a visiting professor in materials science. Now manager of the Materials and Corrosion Program in the Nuclear Power Division, Roberts also is the author of a newly published textbook, *Structural Materials in Nuclear Power Systems* (Plenum Press, New York, 1981). Roberts holds BS, MS, and PhD degrees in metallurgy from Manchester University (England).

Barry Syrett joined the Materials Support group of EPRI's R&D staff in June 1979. He is manager of research dealing with aqueous corrosion, largely in fossil-fueled power plants. Previously with SRI International for nearly seven years, Syrett initiated and developed a program of corrosion research there. He also specialized in corrosion mechanisms and design remedies during earlier work with The International Nickel Co., Inc., and Canada's Department of Energy, Mines, and Resources. Syrett earned BS and PhD degrees in metallurgy at the University of Newcastle upon Tyne (England).

■

People who understand mathematical relationships design models to simulate energy-economic processes. People who make corporate decisions often turn to those models for assistance.

The Meaning Behind the Models (page 14) describes EPRI research to identify and remove the barriers between modelers and users. Jenny Hopkinson, *Journal* feature writer, turns to project participants for their viewpoints and to EPRI's Richard Richels for information on the research scope.

Since August 1976 Richels has been a project manager in the Energy Analysis and Environment Division, specializing in model assessment and decision analysis. Earlier he was a consultant to Rand Corp. and to the office of energy R&D in the National Science Foundation. Much of his work has addressed the influences of uncertainty on the planning and conduct of energy research. Richels holds a BS in physics from the College of William and Mary, an MS in industrial engineering from Columbia University, and an MS and a PhD in operations research from Harvard University.

■

Things familiar are often taken for granted, and this is perhaps one reason the performance of pulverized-coal plants has not improved in recent decades. But familiarity also means there is a firm technologic base for the design advances that EPRI is now bringing together in a new, integrated plant design.

Advancing Pulverized Coal (page 18) reviews the R&D premises, sets forth the objectives that have been established, and enumerates several of the specific developments that will be required. Science writer William Nesbit is the author, aided by Dan Giovanni and Anthony Armor of EPRI's Coal Combustion Systems Division.

Giovanni has been with EPRI since December 1977 and is now manager of the Air Quality Control Program. One R&D concern is to optimize the energy requirements and performance of environmental control systems, which detract from overall plant efficiency. Before coming to EPRI, Giovanni was with Kaiser Aluminum & Chemical Corp., pursuing efficiency in fabrication processes. Still earlier he was with KVB, Inc., as a consultant to electric utilities and power equipment manufacturers, where he was involved in the measurement and correction of emissions and performance problems. Giovanni holds BS and MS degrees in mechanical engineering from the University of California at Berkeley.

Armor, on the staff of the Fossil Plant Performance and Reliability Program since September 1979, manages research on plant designs that integrate various systems and auxiliaries for better overall operation. Between 1968 and 1979 Armor was with General Electric Co. as a technical leader in turbine generator development and design and ultimately as program manager for superconducting generators. Armor holds a BS in mathematics and an MS in mining engineering from the University of Nottingham.

■

Feature writer Jenny Hopkinson—**On-Line Information** (page 24)—describes the workings and management of a computer-based system that has occupied EPRI's Kenton Andrews since 1974. The information on-line goes back to 1960 and is current up to last month.

Andrews is manager of the Electric Power Database–Research and Development Information System (EPD–RDIS). Documentation of companies and their programs, especially for electronic access, has been his specialty for nearly 25 years. Before joining EPRI, Andrews established a corporate data bank for Lockheed Aircraft Co. Earlier he was with TRW, Inc., developing an information management system for an Army helicopter program; with Aerospace Corp.; and with TRW's Space Technology Laboratories. Andrews also has been a consultant to international agencies. A graduate of Pomona College, he has an MS in library science from Columbia University.


Roberts Syrett


Armor Giovanni


Richels


Andrews

CORROSION

The flow paths of hot gases, steam, feedwater, and coolant in a power plant are wide-open avenues for corrosion. Stresses of high temperature and high pressure employed for better thermal efficiency aggravate the problem. New alloys, altered feedwater chemistry, and reduced stress are the design remedies coming from corrosion R&D.

Corrosion, by simplest definition, is the effect of unwanted chemical reactions on metals. For example, metal is eaten away from a structural element until it fails or oxides build up inside a pipe until it is plugged. In a gaseous environment, such chemical reactions occur directly. In a liquid setting, the stimulus of these reactions is electrochemical, a difference of electric potential between metals or between sites on one metal. An anode and a cathode are thus established, and their common liquid environment serves as an electrolyte. Just as in a battery, electrons flow in one direction, current flows in the other; permanent chemical change results, and the anode site is the loser.

Problem and opportunity

Corrosion is pervasive. The fluids that flow through a plant are continuously changing in temperature, pressure, state, and (as a result) composition. The variations make for an exhaustive succession of possible corrodents. Pipes, valves, ducts, heat exchangers, turbines, pumps —all are their targets.

Corrosion is also expensive. One EPRI scientist makes the wry observation that "corrosion is the basis for the spare-parts business behind every industry in the country." Power industry experience supports the point. In the opinion of experts, half the annual maintenance expense for power plants is traceable to corrosion. This single phenomenon, in its many manifestations, costs electric utilities well over $1 billion a year.

To the R&D scientist, metallurgist, or plant chemistry specialist, there are at least eight varieties of corrosion that differ enough to categorize. Names for these varieties briefly describe either how or where the corrosion tends to occur: galvanic, uniform, crevice, pitting, erosion, dealloying, intergranular, and stress. All are described in more detail below.

There are about as many ways to combat corrosion, although they do not directly correspond to the causes.

Among them are to use purer metals or different alloys, to add coatings (organic or inorganic), and to substitute nonmetallic for metallic materials. It may be possible to lessen or avoid corrosion by providing cathodic protection, redesigning for lower service stress, or altering the environment to reduce its corrosiveness.

"Solving corrosion problems is a negative approach," says an EPRI chemical engineer who works with advanced thermal power cycles. "Developing metals and fluids that will function together and permit us to use the inherent efficiencies of high temperature and pressure—that's the positive approach."

EPRI's many R&D projects in corrosion control, remedies, resistance, and avoidance (mostly for application in generation equipment) are an approach from the positive side. In the Nuclear Power Division alone, the effort costs more than $20 million a year, including the urgent corrosion-related work of two reactor owners groups managed by EPRI. In the Coal Combustion Systems and Advanced Power Systems divisions, the annual corrosion R&D expense is about $3 million. Much of this budget, relevant to present and future fossil-fueled plants (as well as to fuel cell and geothermal power units), is managed by the Materials Support group in the staff of the Institute's vice president for R&D.

Three corrosion paths

Power plants whose generators are driven by steam turbines afford a clear context for reviewing important corrosion phenomena. Fueled by coal, oil, or uranium, these plants are the utility workhorses. Many of them produce baseload electricity around the clock; others, especially oil-fired plants, pick up much of the additional, intermediate load each day. In such plants, there are three major fluid flow paths where dynamic combinations of metals, environments, and stresses are interrelated and where they produce the most varied and destructive corrosive effects.

- In fossil-fueled steam plants, the path of combustion gases from the heat radiation zone (the fire side of the boiler tubes) into the heat convection area (superheaters and reheaters), past fans, into ductwork, through flue gas cleanup equipment, and up the stack
- In all steam plants, the path of steam through turbines and reheat loops (the steam side), to be condensed to feedwater and pumped back into its heat source—the fossil-fueled boiler, the BWR core, or the PWR steam generator; also, in a PWR plant, the separate path of pressurized coolant between the reactor core and the steam generator
- In all steam plants, the path of cooling water from its source through the condenser and on to its discharge point (or closed-loop cooling tower)

The path of fossil fuel combustion gases is a special corrosion area only briefly acknowledged in this review. Dry corrosion processes are possible as combustion gas temperature drops in successive heat exchangers beyond the boiler, but the principal problems are associated with wet scrubbers. As Barry Syrett of the Materials Support Group puts it, "The gas is saturated with moisture when it leaves the scrubber. Very little cooling is needed to make it condense, and the condensate is largely sulfuric acid, which can severely corrode carbon steel ductwork."

One remedial technique is called cyclic reheat. This entails heat exchangers upstream and downstream from the scrubber to extract heat that would otherwise be lost in the scrubber and return it to the saturated gas stream, thus countering its tendency to condense. Cyclic reheat is still in its infancy in the United States. It offers the potential benefit of reducing fuel costs because it would replace the reheat burners now used to prevent condensation and to make flue gas more buoyant as it leaves the stack.

Materials used in flue gas ducts and cleanup equipment are a subject of emerging concern in EPRI's Coal Combustion Systems Division. Chemical additives are not the automatic choice to inhibit corrosion; the chemicals already present in stack emissions are enough of an environmental problem.

Thorough R&D in scrubber processes and their chemical reactions will provide a basis for identifying construction materials that have adequate corrosion resistance and reliability. "The search isn't simple," Syrett points out. "More chloride in coal means more hydrochloric acid in the flue gas and more chloride in the scrubber liquor. A previously adequate alloy is suddenly useless. It falls apart." One of EPRI's tasks is to determine the most cost-effective construction materials for scrubbers, recognizing that variations in process control, gas composition, and scrubbing medium influence corrosion-related properties of the scrubber environment (e.g., pH, chloride level, oxygen content). Surface coatings, if they work, could be an inexpensive solution in at least some instances.

Protecting the feedwater

The second major fluid flow path in a steam plant is the steam-feedwater circuit. This is the path of the working fluid, the force that turns the turbines and the electricity generator coupled to them. The transition from steam to feedwater occurs at the condenser, where only the thickness of a heat transfer surface separates the feedwater from the cooling water. The condenser is therefore the first line of defense against corrosion in the steam-feedwater circuit.

The condenser is also a very vulnerable point because it operates at negative pressure, under vacuum. Corrosion here, if it produces a tube leak, permits cooling water with its tremendous range of impurities to be sucked into the feedwater.

There are many examples of condenser inleakage and its effects. Prominent among them is the corrosive attack by sodium and magnesium chlorides in seawater coolant. It can penetrate copper alloy tubes, failure of which permits the chlorides to figure in other forms of corrosion in the feedwater-steam circuit, such as hydrogen liberation and attack on drum-type boilers of fossil-fueled plants; corrosion product buildup and consequent deforming forces on steam generator tubes of PWR plants; stress corrosion cracking of small-diameter coolant pipes in BWR plants. Chlorides, hydroxides, and other contaminants also pass into turbines, and as steam condenses there, the contaminants combine with the condensate to cause stress corrosion cracking of turbine disks (mostly in nuclear plants) and stress corrosion and corrosion fatigue of turbine blades (mostly in fossil-fueled plants). The different principal sites and types of corrosive attack are the result of different temperature and pressure conditions and of different feedwater chemistries.

It is doubtful that condenser leaks can be totally prevented. There are tens of thousands of tube assembly joints, and the leaks at these junctions are not entirely the result of condenser corrosion. R&D attention to leak-tight condensers is mainly to remedy corrosion processes in the boiler and turbines, not in the condenser itself.

The ends of condenser tubes pass through walls known as tubesheets and are secured there by a rolling process—revolving a mandrel in each tube end to deform it radially against the hole. Such joints may be further sealed by welding. Welding is costly and may not completely prevent leaks because corrosion acts as an electrochemical wedge into any fine crevice on the cooling-water face of the tubesheet.

A promising solution being developed under EPRI auspices is kinetic bonding. This technique employs an explosive charge that virtually fuses the tube and tubesheet metals. The cost is more than \$5 per shot, but kinetic bonding should be commercially feasible if its unit cost can be brought down to about \$1. Considering \$150,000 or more (at the lower

CORROSION CATEGORIZED

Galvanic corrosion is the most fundamental type, in which a difference in electric potential exists between two metals or between a metal and a nonmetallic conductor. A liquid electrolyte connects them to permit current flow, and the batterylike action eats away the less resistant (anodic) metal.

Uniform corrosion involves current flow between different sites on a single metal, causing a wide area of metal to be progressively corroded. In terms of sheer metal tonnage lost, this is the dominant corrosion type. It is also predictable and, in less exacting applications at least, it is easily circumvented or inhibited by design changes or accepted and solved by the frequent replacement of parts.

Crevice corrosion occurs in spots that are somehow shielded from full exposure to the environment, such as under deposits or at the junction of overlapping metal parts. If a fluid stagnates there, its composition and electric potential become sufficiently different from the normal to set up corrosive action. Pitting is also a localized corrosion, which originates at susceptible sites on the surface of some alloys that resist uniform corrosion. The characteristic holes become deeper and the action more severe as corrosion products become concentrated in the bottom of the pit.

Erosion corrosion combines two phenomena, each accentuating the other. High-velocity fluids, turbulence, and suspended solids have an erosive effect on a metal surface. If a protective oxide film is thus removed, corrosion may begin. Continued erosion removes any oxide that may tend to form again, and a vicious circle of cause and effect proceeds.

Dealloying denotes the selective parting of metals in an alloy. In brass, the preferential corrosion of zinc is called dezincification; it leaves a copper-rich surface layer. When cast iron corrodes selectively, the surface layer becomes rich in graphite (carbon).

Intergranular corrosion occurs at the boundaries (anode) between grains (cathode) of steel. Little metal substance is lost as boundary material is eaten away, but the effect is profound because that material is the glue that holds the grains together.

Stress corrosion occurs when localized mechanical stress upsets the uniform character of a metal, for example, causing a break in the protective oxide on an alloy. This corrosion is insidious because the continued presence of stress may cause a structural crack to form and slowly propagate. Applied stress (a known quantity in product design) need not be entirely to blame. Residual stress often contributes significantly; this is stress locked into the metal by welding heat (most frequently), by differential stress (cold working) in the course of the metal's fabrication or functioning, or by the rapid heating and cooling of massive components. □

cost) for kinetically bonding all the tubes of a single large condenser installation, EPRI's 1981 commitment of $500,000 for continued development by Lockheed Missiles and Space Co., Inc., is well worthwhile.

Erosion corrosion is also a problem in condensers because of turbulent flow conditions. Attention to flow patterns during equipment design is a possible remedy. Adding ferrous sulfate to the cooling water has some inhibiting effect on the corrosion of copper alloy tubes, and EPRI is investigating Japanese and European experience with this approach. Cathodic protection may be useful here too; so far it has been used only infrequently in U.S. condensers to prevent galvanic corrosion when a waterbox, tubesheet, and tubes are of dissimilar metals (e.g., cast iron or steel, copper alloy, and titanium, respectively).

A more serious corrosion problem is posed by sulfide pollution in the cooling water. Only 10 parts per billion (ppb) can attack copper alloys, whereas the water may contain 200 ppb, a concentration with a distinct odor. Sulfides can also evolve from the decay of organic matter trapped in a condenser during shutdown. Experiments have shown that sulfide action can corrode ¼-inch-deep pits in copper-nickel alloy in four months. This is a strong argument for titanium or stainless steel tubes. The former are standard for nuclear plant condenser designs in France and Japan today.

Although titanium tubes seem to be immune to sulfide attack, their installation in a copper alloy tubesheet calls for cathodic protection of the tubesheet. And the use of cathodic protection becomes tricky when cooling water quality fluctuates. Control of galvanic corrosion may call for one cathodic current level when the water is not polluted, and a much higher level when sulfide levels are high. That extra current may induce another adverse effect, a liberation of hydrogen from the water and its formation as a hydride layer on the titanium. When this happens, the tubes may be embrittled and weakened. No failures have occurred in condenser service, but EPRI is studying the tendency toward hydriding as a function of sulfide levels and cathodic protection.

Treating the feedwater

Justifying a proposed EPRI research project, Barry Syrett wrote, "Boiler tube failures account for the largest percentage of forced outages in most utilities. About 67% of all tube failures are in the highest heat flux area of the waterwall, and about 20% of these are caused by waterside corrosion." This is a picture of fossil-fueled plant experience.

Corrosion is comparably serious in the secondary loop of PWR plants, where a steam generator takes its heat from the fission-heated water of the primary loop instead of from fuel combustion. Crevice corrosion attacks the junctions of steam generator tubes and their support plates. Magnetic iron oxide builds up between the outside of the tube and the inside of its hole in the plate. The growing deposit squeezes the tube and can rupture it. The problem then is not passage of corrodents into the primary loop, but passage of radioactivity out of the primary loop. The comparable problem in a BWR plant arises at the condenser because there is just one fluid loop connecting the core, the turbines, and the condenser. The radioactivity is carried by dissolved iodine and other species.

Given that condensers will leak, it is necessary to deal with the corrosion triggered in boilers, steam generators, turbines, and elsewhere by inleaking corrodents. Research must consider the stresses, materials, and environments in each major area of corrosion. In a fossil-fueled plant, for example, the example of hydrogen attack in boilers has been mentioned. This problem is caused by chloride delivered from the condenser, accumulating beneath deposits, and creating an acid condition that liberates hydrogen. Absorbed by boiler tube surfaces, the hydrogen creates an embrittled condition, and the tube eventually ruptures.

For both fossil-fueled and nuclear plants, a first approach to suppressing chloride and other feedwater contaminants is feedwater treatment and control. But this step has its limitations. Even a full-flow condensate polisher, while removing certain ions from the entire feedwater stream, may release other compounds from its demineralizers. The important distinctions between drum-type and once-through boilers also reveal why there is no single avenue of corrosion control through feedwater chemistry.

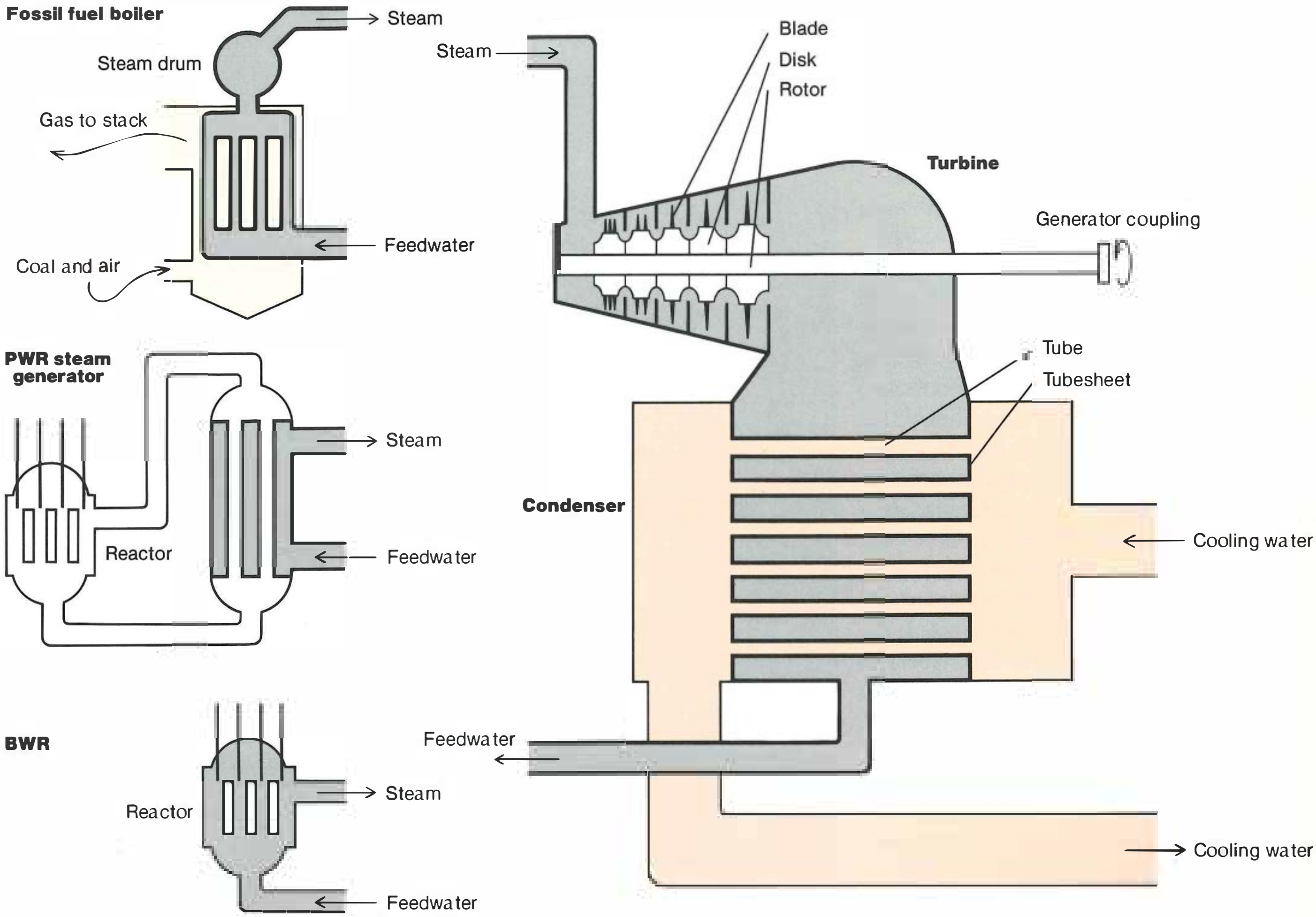
A drum-type boiler delivers a mixed-phase fluid (liquid and vapor) through its tubes to the steam drum above. Pure steam separates from the water in the drum and the water recirculates to the boiler. Feedwater for such a boiler need not be absolutely pure. Additives are used to control pH and oxygen content. For example, coordinated phosphate treatment holds pH in a range of 9.8–10.2, which is below the threshold of tube corrosion.

Phosphates are a mixed blessing. There is some opinion that phosphate carryover in the steam is a corrosion inhibitor throughout the feedwater-steam loop. There is also the recognition of caustic gouging of boiler tubes, a phenomenon found beneath deposits caused by highly alkaline ($pH > 10$) phosphate concentration in the pores of the deposits.

A once-through boiler has no drum and no recirculating feedwater. The entire fluid flow enters the boiler tubes as a liquid and goes on to the turbine as a gas. The water must therefore be very pure, or all its additives must be volatile. As an example of purity standards, even a few ppm of sodium chloride will tend to precipitate at the point in the tube where its carrier water vaporizes, and a corrosive deposit will build up at that transition. As examples of volatile additives, ammonia is used in a once-through

Corrosion is caused by unknown or unplanned changes in chemical and stress conditions along the major paths of fluid flow in a power plant. Targets of corrosive attack include many more components than the alternative steam sources (fossil fuel boiler, PWR steam generator, BWR), turbine, and condenser shown here.

The steam path through the turbine is especially vulnerable to corrosion because the fluid is condensed and recirculated as feedwater to the steam source. Moreover, the partial vacuum in the condenser, created for thermal efficiency, tends to suck air and cooling water through every joint and tiny crack. Components at risk include steam superheaters and reheaters, condensate pump, feedwater heaters and pumps, makeup water demineralizer and evaporator, and boiler feed pump.



boiler for pH control, and hydrazine is added to reduce the dissolved oxygen content.

Three-pronged attack

The primary coolant recirculation piping of a BWR is exposed to much the same environment as a boiler. Intergranular stress corrosion cracking (IGSCC) in some such piping, first noted in 1974, has led to extensive and urgent corrective efforts. According to Adrian Roberts, materials scientist in EPRI's Nuclear Power Division, this is one of a very few examples where the metal, the stress, and the environment have all been addressed through research.

"An image of three overlapping circles is helpful in visualizing remedies for stress corrosion," says Roberts. "The unwanted IGSCC phenomenon takes place only in the area common to all three circles, that is, only under some of the possible conditions of metal alloy, stress value, and water composition, and those only in combination. Incidentally," Roberts adds, "don't visualize the circles the same size. The relative importance of the three factors is different from one component to the next."

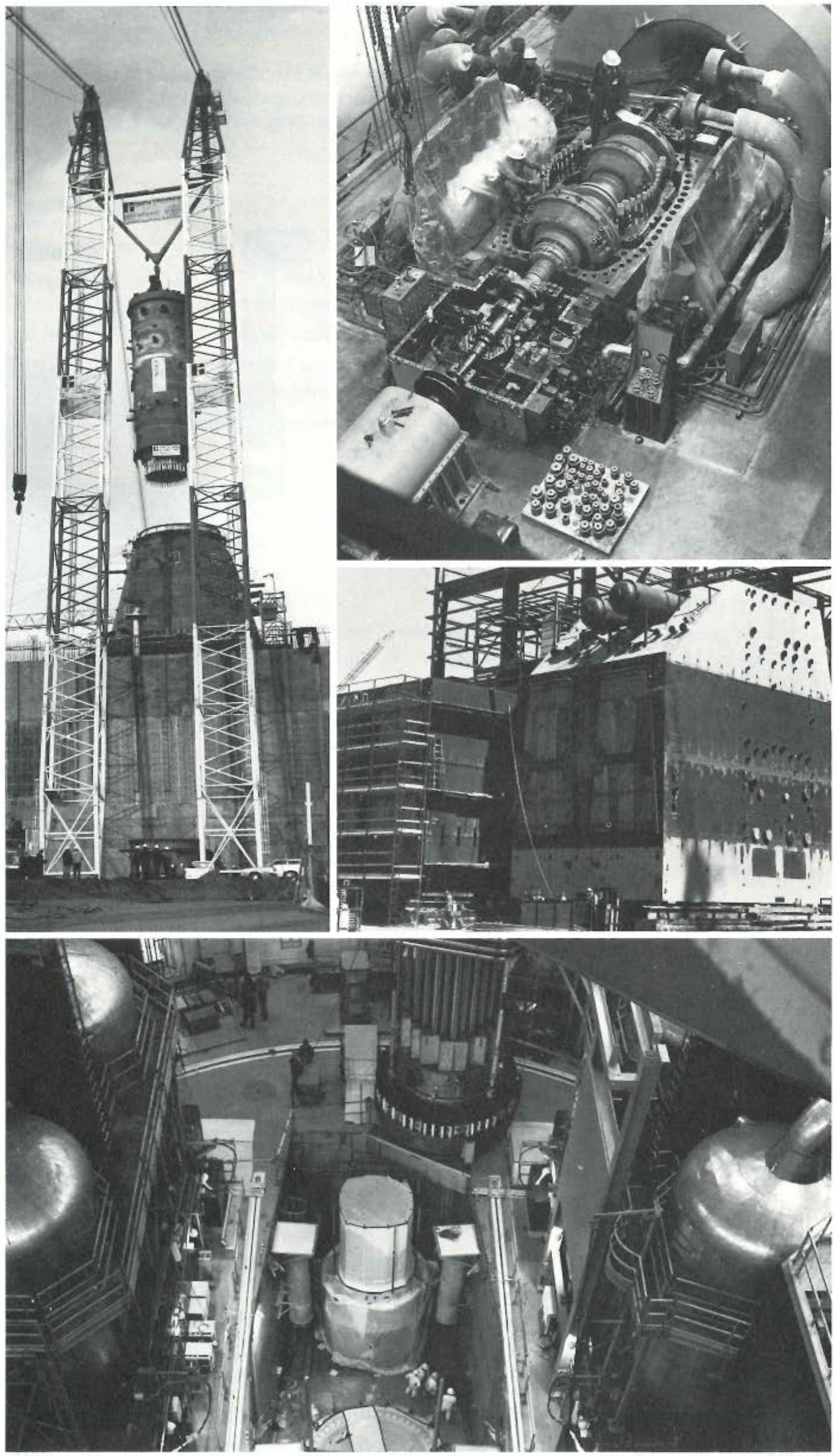
Alloy composition was the first topic of investigation in solving BWR pipe cracking. The traditional type-304 wrought stainless steel piping of BWRs is generally resistant to corrosion because of its 17% chromium content and the passivating oxide layer, which acts as a corrosion barrier. However, the heat of the welding causes chromium carbide to precipitate. This lowers the chromium content below 12% at grain boundaries, thereby making the steel more susceptible to IGSCC.

The research objective was to design an alloy that would not be affected in this way. The results were two stainless steel variants, called type-304 nuclear grade and type-316 nuclear grade, the latter now favored for new construction. These alloys have tighter specifications on metallurgical conditions (e.g., hardness, grain size) and upper limits on nitrogen content (0.1 wt%) and carbon content (0.02 wt%).

Reduction of residual stress in welds was another avenue toward crack prevention; this is now being explored by the BWR Owners Group and EPRI. Two techniques have been investigated: induction heating stress improvement and last-pass heat sink welding. Both techniques change the distribution of residual stresses in welds, and this should inhibit both the formation and the propagation of cracks, resulting in longer pipe life. The effectiveness of induction heating has been conclusively demonstrated in new pipes, less so in pipes that have begun to crack. Neither technique has been unequivocally recommended to utilities for retrofit because the degree of efficacy and reasonable benefit-cost ratio have not yet been thoroughly defined.

The nature of the corrosion environment behind IGSCC in BWRs is a special case. Radiolysis of water in the primary loop of any nuclear power plant produces free hydrogen and oxygen. The oxygen is a corrodent and must be purged. Three approaches are tentatively being proposed, two for plant startup and shutdown and one for steady operation.

Deaeration (introduction of a vacuum condition) is for startups, when oxygen levels tend to be high, along with increasing temperatures and thermally induced stresses. Deaeration can pull the oxygen level down from 8 ppm to 0.2 ppm. Laboratory data indicate it is effective for inhibiting corrosion; field data are not as conclusive. The discrepancy may be traceable to the fact that cumula-



The major elements of a steam electric power plant are large and complex; expensive to build, install, and repair; and susceptible to corrosion. Corroded components are difficult to get at and costly to replace. Even more important, when a power unit is out of service, replacement energy must come from another unit that is more expensive to run.

tive startup times represent a very small interval of total plant operation as it is measured in the field. But cumulative startups represent most of the time involved in laboratory tests.

Nitrogen blanketing (displacing oxygen above the water surface) is another way to reduce oxygen content; it is most effective when a plant is being shut down. Hydrogen injection, the third technique, reduces oxygen to the 3-ppb level, where no cracking from this cause is possible. Hydrogen injection has been tested only for short periods (no more than a week) in Sweden. Further tests planned for 1981 in Sweden and in this country will extend to at least a month.

Effects in turbines

Although superheater and reheater tubes of fossil-fueled plants seldom fail from fire-side corrosion, they (and the main steam piping) are susceptible to oxidation and the formation of scale on the steam side. When scale particles break loose (spall) and are blown into the turbine, they cause serious wear (hard-particle erosion) on nozzles and early stages of blading. Chromate treatment of tubes and steam lines results in a thinner, more tenacious scale, which is less likely to spall. Altered thermal patterns in startup and shutdown and during cycling are also partial answers. So may be wear-resistant coatings for turbine blades.

In nuclear power plants, turbine inlet steam conditions are about 530–580°F (275–305°C) and 950–1000 psi (6.5–6.9 MPa). In a fossil-fueled plant, analogous figures may be 1000–1050°F (540–565°C) and 2400 or 3500 psi (16.5 or 24.0 MPa). Water chemistries differ too, with the result that different corrosion types generally prevail at different points along the steam path through the turbines.

Stress corrosion cracking is a threat to the disks of turbine rotors, especially in nuclear plants. (The disks carry the turbine blades.) Steam typically begins to condense at about the second row of blades in the low-pressure turbine stage. If salt water contaminants have entered the feedwater-steam circuit at a leaky condenser, here is where (in a wet environment) they will attack the low-alloy steel of the disks.

Steam condenses farther along the low-pressure turbine of a fossil machine because steam temperature and pressure are initially higher. Condensation usually centers in the next-to-last row of stainless steel blading. The most likely and troublesome agent in this case is acidic chloride, causing stress corrosion and corrosion fatigue. Blades and their attachments are the major targets. Titanium blades are an alternative developed under EPRI sponsorship. They resist this corrosive attack and are expected to see wide use in retrofit as well as in new designs.

The value of a cure

Estimates of the annual cost of corrosion in utility generating facilities are dramatic but uncertain—like the $1 billion cited earlier. More tangible is the cost of a single day of forced outage for a large power plant and the cost of a remedial measure.

Outage cost is the difference in cost between the machine that is down and the machine that replaces it. The latter is assumed to be the next most expensive unit, that is, the next one a utility would put on-line to meet an increase in demand.

Fuel, rather than spare parts and repair services, dominates the comparative figures today. Reasonable fuel costs early this summer were 8 mills/kWh for nuclear, 23 mills for low-sulfur coal, and 65 mills for oil. The differential prices, compared with nuclear fuel, were 15 and 42 mills, respectively. Assuming in each case a 1000-MW plant with an 80% daily capacity factor, the daily cost differences are $228,000 (coal replacing nuclear) and $806,000 (oil replacing coal).

There are even some utilities in the northeastern United States where oil-fired plants would replace baseload nuclear power. In such an instance, these figures yield an energy replacement cost of more than $1 million per day. Certainly, $500,000 per day would be a conservative average figure.

Titanium condenser tubes are one example of a remedy for significant corrosion. For a 1200-MW nuclear plant installation of 150,000 tubes, using titanium instead of copper-nickel alloy would cost an additional $4–$5 million. Such a condenser would pay for itself if it added 10 days availability during the plant lifetime.

But condenser corrosion of itself does not justify the changeover to titanium. Hundreds of leaking tubes can be plugged without appreciable effect on condenser performance. Further, most condensers are modular, and plugging can be done while the power unit continues to operate at reduced load.

Far more important are the corrosion and related damage in steam generators and turbines that follow feedwater contamination at a leaky condenser. Precise cause-and-effect relationships are difficult to document because plant duty, operating practices, feedwater control, and other variables all play their parts. But turbine repair outages, for example, the replacement of a rotor, take 4–6 weeks, and at the cited figures for replacement energy, they can cost $14–$21 million. Seen in this context, the R&D to avoid major generating outages caused by corrosion is a bargain. ■

Further reading

Construction Materials for Wet Scrubbers. March 1981. EPRI CS-1736 (2 Vols.).

Corrosion-Related Failures in Power Plant Condensers. August 1980. EPRI NP-1468.

M. Fox. "Progress in Fighting BWR Pipe Cracks." *Power,* Vol. 125, No. 8 (August 1981), pp 53–56.

R. I. Jaffee. "Metallurgical Problems and Opportunities in Coal-Fired Steam Power Plants." In *Metallurgical Transactions A,* Vol. 10A, No. 2 (February 1979), pp 139–164.

J. T. A. Roberts. *Structural Materials in Nuclear Power Systems.* New York: Plenum Press, 1981.

This article was written by Ralph Whitaker. Technical information was provided by Adrian Roberts, Nuclear Power Division, and Barry Syrett, Materials Support.

The Meaning Behind the Models

Understanding the relationship between energy-economic issues and the computer models used to describe them can be problematic . . .

Computer modeling can assist policymakers in making their decisions. While not a replacement for intuitive judgment, the more structured approach of a model provides a way to synthesize large quantities of data and to articulate and transfer information quickly and efficiently. Yet despite the possible benefits, computer modeling in the past has not been used to its fullest potential. Poor communication between the fields of model development and policymaking has impeded the use of models in the policymaking process.

To bridge the gap between modelers and users, and thereby encourage a free exchange of opinions and outlooks, EPRI has inaugurated three complementary projects, each of which improves the transfer of modeling concepts and the communication of policy issues.

Of these three, the Energy Modeling Forum (EMF), was created to study specific energy issues, and another—the Utility Modeling Forum (UMF)—was organized to pool the practical experience of utility model users. A third—the Model Assessment Program at the Massachusetts Institute of Technology—was established to evaluate the capabilities, limitations, and realism of individual models.

All three projects are managed by EPRI's Energy Analysis Department staff, who provide information, analyses, and models focused on the economic aspects of energy issues to three distinct groups: analysts at electric utility companies, R&D planners at EPRI itself, and national and regional policymakers in the public sector.

Although the three groups have a different orientation, they have one procedure in common—each uses information and analyses produced by computer-based mathematical models. As Richard Richels, project manager in the Systems Program, describes the benefits of this procedure, "Modeling can be extremely valuable in providing general insights into a problem. Often results that appear puzzling at first glance can lead to a reassessment of ideas and a deepening of understanding. But experience has shown that without the rationale behind the numbers, users tend to have little use for results that do not conform with their own intuitive judgments."

Until recently, Richels explains, insufficient attention was given to communicating the pathways to results, so the Systems Program initiated two types of model analysis activities to help its client groups better understand model-based results: on the one hand, analyses focusing on issues and on the use of models in probing those issues, and on the other hand, analyses focusing primarily on the model itself. The studies of EMF and UMF are of the issue-oriented type, whereas the work done by MIT's Model Assessment Program is of the model-oriented type.

The EMF

The aim of EMF analysis is to broaden the user's insights and understanding not only of model but of policy issues, too. EMF, whose director is James L. Sweeney, a professor in engineering-economic systems at Stanford University, is cofunded by DOE, EPRI, and the Gas Research Institute and operates through ad hoc working groups of energy model developers and users. Many models are applied to a single subject of inquiry at each forum, which is usually attended by about 40 people. (Participants attend three or four EMF meetings for a couple of days every three months over a nine-month period.)

At a recent meeting, for instance, 10 models were compared in an analysis of coal production, distribution, and utilization (Coal in Transition: 1980–2000); and at another, 18 models were run in a study of the response to variations in the prices of oil, gas, coal, and other energy sources (Aggregate Energy Demand Elasticities).

One participant, J. Michael Gallagher, assistant to the vice president and manager, research and engineering, Bechtel Group, Inc., commented on the coal study, "The most direct benefit was the interchange of ideas among the policy modelers. . . . It's an unusual opportunity to see the thinking of a modeler get translated into the model. It was also refreshing to hear all the questions the nonmodelers have about the models."

Since EMF was formed in 1976, six studies have been made: Energy and the Economy, Electric Load Forecasting, U.S. Oil and Gas Supply, World Oil, and the two already mentioned on coal and energy demand elasticities.

Gina Despres, legislative assistant to Senator William Bradley, attended the World Oil forum and commented, "It was extremely useful to have the models subjected to rigorous scrutiny, to penetrate their underlying assumptions, and to put their conclusions into perspective. It alerted one to the degree of uncertainty that decision makers face."

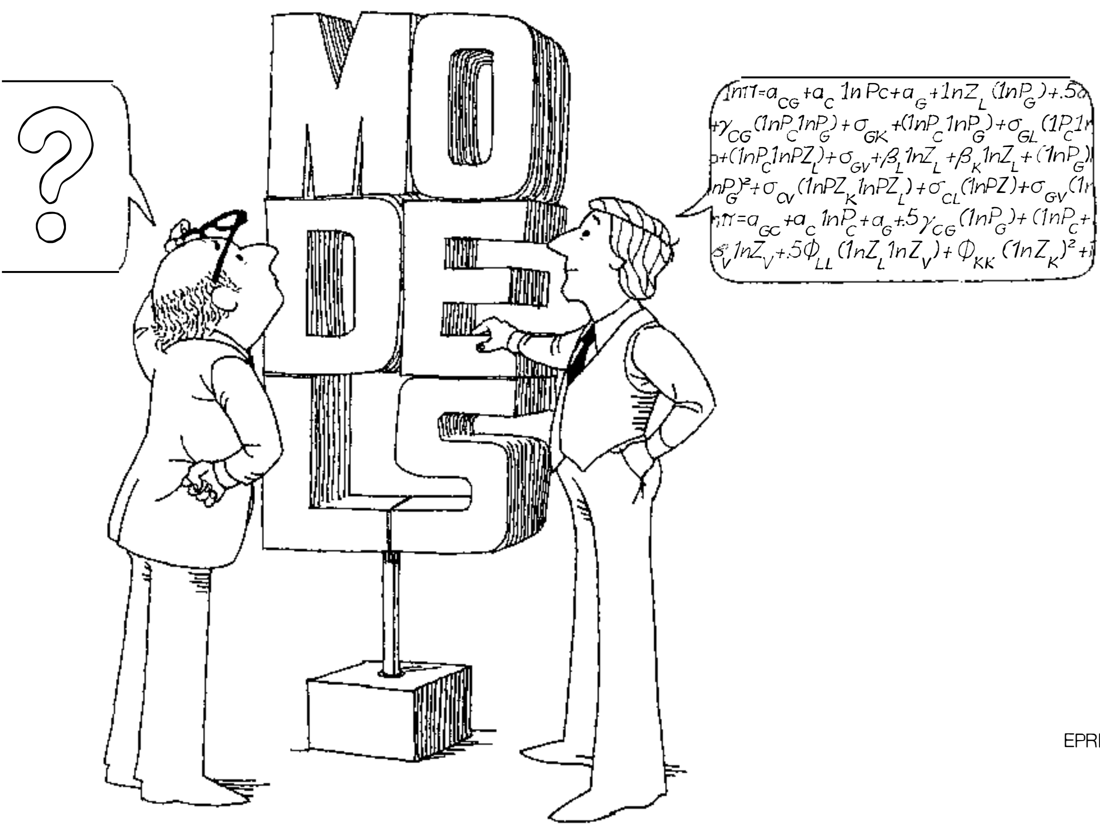
The next study, Energy Shocks, will focus on the short-term energy-economic effects of possible foreign oil cutoffs. This will be in contrast to the long-run issues examined in the first study on energy and the economy, which were based on the question "Suppose we gradually run out of domestic oil and gas. The population grows, and with it, demand. What will be the economic impact?"

In the first study, the answers threw light on policy issues, such as choices to be made between various R&D proposals. But it also became apparent that EMF participants were even more concerned about short-term phenomena, for example, a Middle East oil cutoff that instigates a steep rise in oil prices, which, in turn, requires a series of short-run adjustments in the energy-economic sector. Hence, the newest topic of study, Energy Shocks, is now being organized.

John Weyant, deputy director of EMF at Stanford University, outlined another topic, which was debated at the forum on energy demand elasticities: "A low elasticity figure means that there's not much flexibility in the economy to substitute for energy. Reduced energy availability and higher prices may lead to a dramatic reduction in GNP. On the other hand, if the elasticity figure is very high, it implies that there is great flexibility and capability for energy substitution—for example, with insulation, heat recuperators, alternative energy sources, different processes, or greater use of capital and labor."

In that study, two types of models were run: statistical models and judgmental (or intuitive) models. Weyant explained that most of the modelers present produced very different aggregate figures for elasticity. "The statistical models came up with a relatively high figure and the judgmental models resulted in a relatively low one." One of the participants, Roger Naill, a DOE policy staff member responsible for much of the analysis behind National Energy Plan II, considerably revised his judgmental estimates as a direct result of taking part in this forum.

Another product of the communication at EMF meetings is the opportunity for modelers to compare their data. Weyant recalled an instance of a modeler noticing that his figure for a particular year 2000 estimate was 50% higher than everyone else's. Tracing it back to its source, he found that his 1981 figure was also 50% higher than his colleagues' data. This discovery set off further investiga-



tion and revealed an early error.

Another instance of the communication at EMF is described by Weyant. "There's an element of the dialectic—forum members are motivated to do a more careful job of explaining what they understand about the problem or the solution to an issue because there are people there who are in a position to affect the way things happen, that is, policymakers."

A lasting product of the EMF process is its group of alumni, some two hundred people who have been actively involved in one or more of the studies. These are people who occupy central positions in their organizations and interact with a large number of additional people, thus disseminating the information generated by EMF.

The broad scope of EMF is also ensured through the input of its Senior Advisory Panel, which is composed of members of Congress, universities, the electric utility industry, the oil industry, the gas industry, and the environmental community. The panel was established after the first study in order to involve the highest levels of government and industry in reviewing EMF studies and suggesting additional topics for comparative analysis.

In the first few years of its operation, EMF was funded exclusively by EPRI. Now that EMF is recognized as a successful institution that contributes to the national energy debate, EPRI is reducing its funding so that EMF may be supported by the many organizations (in addition to EPRI, DOE, and the Gas Research Institute) that benefit from the results.

The UMF

Three years after EMF was formed, UMF was set up by EPRI for modelers and decision makers who work specifically in the electric utilities. Their accumulated expertise in the practical application of utility modeling is a resource that is being fruitfully shared with prospective users in other utilities, as well as with each other.

The core of UMF is a set of working groups, each composed of 20–45 utility model developers and users, and each organized around a broad industry issue, to which UMF applies various utility models. The results of these model applications help participants not only to better comprehend how to model the issue but also to compare the basic structure and usefulness of the models. A panel of senior utility executives, including representatives from EPRI advisory groups, proposes topics for study and subsequently reviews the reports of the working groups.

So far UMF has sponsored two working group studies. The first dealt with four aspects of load forecasting models: quantifying uncertainty in demand projections, load-shape modeling and the effects of time-of-use rates, the impact of new technologies on future load growth, and comparison of econometric and engineering models. The findings of this group provided key guidance to the development of related EPRI research projects and to the formation of a special project to help members of the Rural Electrification Administration enhance their forecasting capabilities.

The second working group dealt with the capability of various types of corporate planning models to analyze the impacts of load management. As in the first group, participants included utility representatives from both public and investor-owned systems.

The UMF program has also sponsored the development of the *Utility Model Notebook,* a review of current utility models, which has been widely distributed throughout the industry.

UMF enables utilities to benefit from

. . . but given a common ground from which to exchange views and information, modelers and decision makers can shed light on each other's fields of expertise discussions of modeling and issue problems, which in many cases turn out to be common experience.

As chairman of the second working group, H. G. Baker, Jr., senior vice president of Georgia Power Co., commented on the value of UMF, "Models mirror reality in many respects. Therefore, as our industry's problems have grown, it is not surprising to find the quantitative tools we use exhibiting a similar trend. Unfortunately, this trend can be counterproductive, forcing utility executives on occasion to have to deal with two imponderables—the real world and their company's analytic simulation of it. . . . Our objectives were worthy, if not idealistic, that is, to gain insights into the strengths and limitations of current corporate planning models and to produce a report that would enhance the ability of model developers and users to communicate more effectively with corporate decision makers. I feel we have made a significant effort toward meeting these objectives, although it is unlikely that we could ever capture on paper the richness of all the insights that came from direct participation in our meetings and debates."

Like EMF, the UMF experiment has proved successful. For the third working group of UMF, EPRI is attempting to attract institutional support from those companies that will be participating directly. It is hoped that EPRI will be able to reduce its financial commitment to UMF without jeopardizing the continuation of this important bridge between utility model builders and users.

Model assessment

At MIT, model assessment consists of taking one model at a time and repeating a number of computer runs to explore the model's capabilities, its limitations, and its realism. To achieve this assessment, the model is checked to see whether it is as advertised in the documentation (verification) and whether it sufficiently mirrors the real-world situation that it is supposed to simulate (validation). The data are scrutinized for appropriateness, adequacy, and accuracy, and the entire model is reviewed for clarity, cost, convenience, and efficiency.

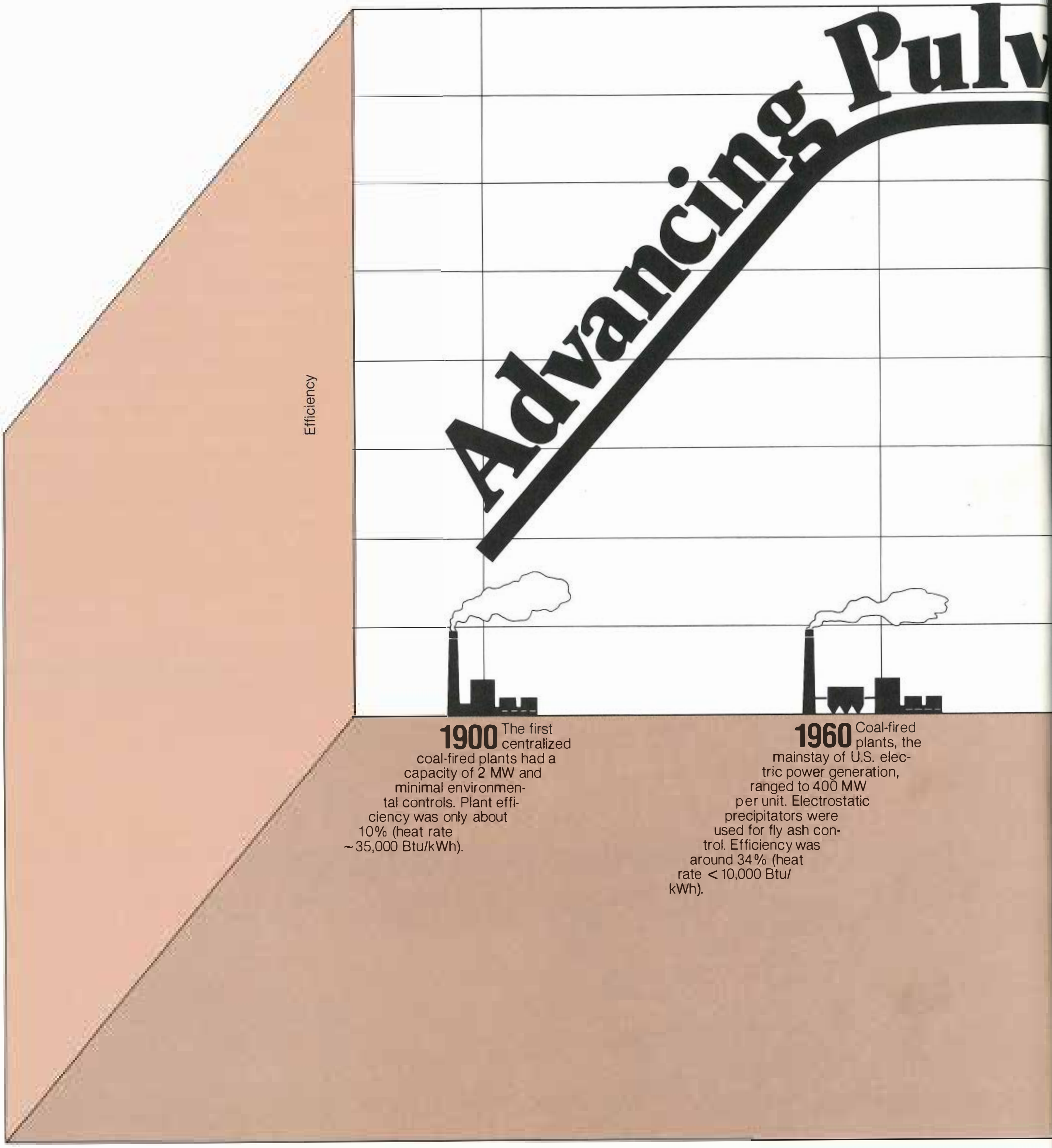
The assessment also includes a characterization of the model's properties. Its assumptions and limitations are examined, as are the reasons for the results it produces. This characterization gives MIT–EPRI analysts a fuller comprehension of the model, enabling them to understand those situations in which the model can be used most appropriately. The assessment also reveals how the model can be revised, extended, simplified, or linked with other models for other operations.

The dual goal of the MIT work is to fit each model more exactly to its assigned mission and at the same time to have enough knowledge of its characteristics to adapt it to some other mission if need be.

Much has been learned about the nature, problems, and possibilities of model analysis from the MIT assessments and the EMF and UMF studies. This convincingly demonstrates that the role of model analysis is essential in making models more useful.

With the continued support and encouragement of model sponsors and users, it seems likely that model assessment and forum analysis will become a permanent and important component of energy modeling, with model users and the public as the ultimate beneficiaries.■

This article was written by Jenny Hopkinson. Technical background information was provided by Richard Richels, Energy Analysis and Environment Division.


Advancing Pulv
Efficiency
1900 The first centralized coal-fired plants had a capacity of 2 MW and minimal environmental controls. Plant efficiency was only about 10% (heat rate ~35,000 Btu/kWh).
1960 Coal-fired plants, the mainstay of U.S. electric power generation, ranged to 400 MW per unit. Electrostatic precipitators were used for fly ash control. Efficiency was around 34% (heat rate < 10,000 Btu/kWh).

rized Coal

Building on an established technology is the idea behind the advanced pulverized-coal plant. Innovations in materials and design will be the keys in breaking through a 20-year barrier to improvement in plant performance.

1980 Coal plant sizes range from 300 to 1300 MW, and environmental controls account for 40% of the plant equipment. Efficiency is still at about the 1960 level f 34% (heat rate 0,000 Btu/kWh).

1990 Capacity of the advanced pulverized-coal power plant will typically be 600 to 800 MW. Integrated environmental control technology will simplify the plant design. Efficiencies of 39% or better are expected to be achievable (heat rate <9000 Btu/kWh).

A key item on the utility industry's agenda for the 1980s is to improve the technology for generating electricity from coal. Conventional pulverized-coal-fired steam power plants are now the workhorses of the industry. The result of over 80 years of design development and improvement, they produce almost half of the electricity generated in the United States today.

But over the past decade the performance of these plants has fallen off in terms of efficiency and reliability. Today, the average pulverized-coal-fired plant is available for service only about 65% of the time, and when it is operating, it performs at an average efficiency of only some 34%, compared with a practical upper limit of about 40%. The significance of this is that there is considerable room for improvement and even small changes represent large dollars; for example, an improvement in plant efficiency from 34% to 37% brings a savings of at least $5 million a year for each 1000 MW (e) of capacity. In addition, fuel is conserved, and environmental control performance is improved.

Four developmental coal-based power generation alternatives are being pursued by EPRI: fluidized-bed combustion, both atmospheric and pressurized; gasification–combined cycle; and a supercritical advanced pulverized-coal plant. (Supercritical operation is operation at steam pressures above 3450 psi; 23.8 MPa.) Of the four, the advanced plant represents a straightforward evolution in present practice—in essence, using new materials and design modifications to accommodate advanced thermodynamic conditions and better use of waste heat.

The evolutionary approach to improved efficiency offers a number of important advantages. It is near term, low risk, and comparatively less expensive in development. It builds on a proven design base tested in 80 years of utility operation and requires no breakthrough in technology; thus costs can be confidently predicted. The benefits of advanced steam conditions developed initially for pulverized-coal application are ultimately applicable to the other three coal-based alternatives as well.

Although these advantages have historically existed, a recent EPRI-funded study has rekindled interest. Among the major conclusions of this 30-month study are the following.

- With a nominal outlay of $25 million for required development work, an advanced pulverized-coal-fired plant could be on order within five to seven years, offering a 10% improvement in thermal efficiency over present commercial designs.
- The plant's improved performance would not compromise reliability.
- Cost savings in the operation of a 750-MW unit (the size selected as optimal in the study) could go as high as $160 million (1978 dollars) over the plant's lifetime (assuming a first-year fuel cost of $1.38/MBtu).

In terms of thermal efficiency, the technology promises a drop in heat rate of as much as 865 Btu/kWh, compared with the most efficient plants commercially available today, as well as less gaseous and particulate emissions because of this improved efficiency. (A lower heat rate means less fuel is required to produce the same amount of electricity.) Capital costs are estimated to be 3–5% more than those for conventional capacity ($800/kW versus $775/kW), but in each of a variety of economic scenarios, this higher cost was always justified over lifetime operation.

Pushing performance

"This may not be glamorous development work," says Dan Giovanni, manager of EPRI's Air Quality Control Program, "and major technical breakthroughs are not required to achieve success. What we're doing is pushing for a 10% improvement in a technology that has been familiar to the industry for a long, long time."

Performance improvement with the advanced pulverized-coal plant comes in two ways: by increasing steam conditions to the higher, supercritical level (which accounts for roughly 40% of the gain) and by incorporating design changes to reduce thermal losses (which account for the remaining 60%). Of the 60%, approximately one-half would come in the form of waste heat recovery and cycle changes or modifications. The other half would come in equipment efficiency improvements.

This diversity of sources for performance gains represents yet another advantage for the approach. It also means that both new and existing power plants can benefit. "The advanced pulverized-coal plant is not an all-or-nothing package," explains Kurt Yeager, director of EPRI's Coal Combustion Systems Division. "Rather, it is a collection of improvements that can be selected and packaged to best meet the site-specific requirements of each utility. Many of these improvements are applicable to both existing and new plants and will improve reliability and longevity as well as efficiency. The advanced plant takes advantage of improvements in design and materials that have occurred over the last 10–15 years, and it complements the other advanced options by providing continued improvement on coal-fired power plant performance and reliability until the potential of those other options can be confidently realized. It also recognizes that the large majority of new power plants to be built, at least to the end of this century, will be of the pulverized-coal variety."

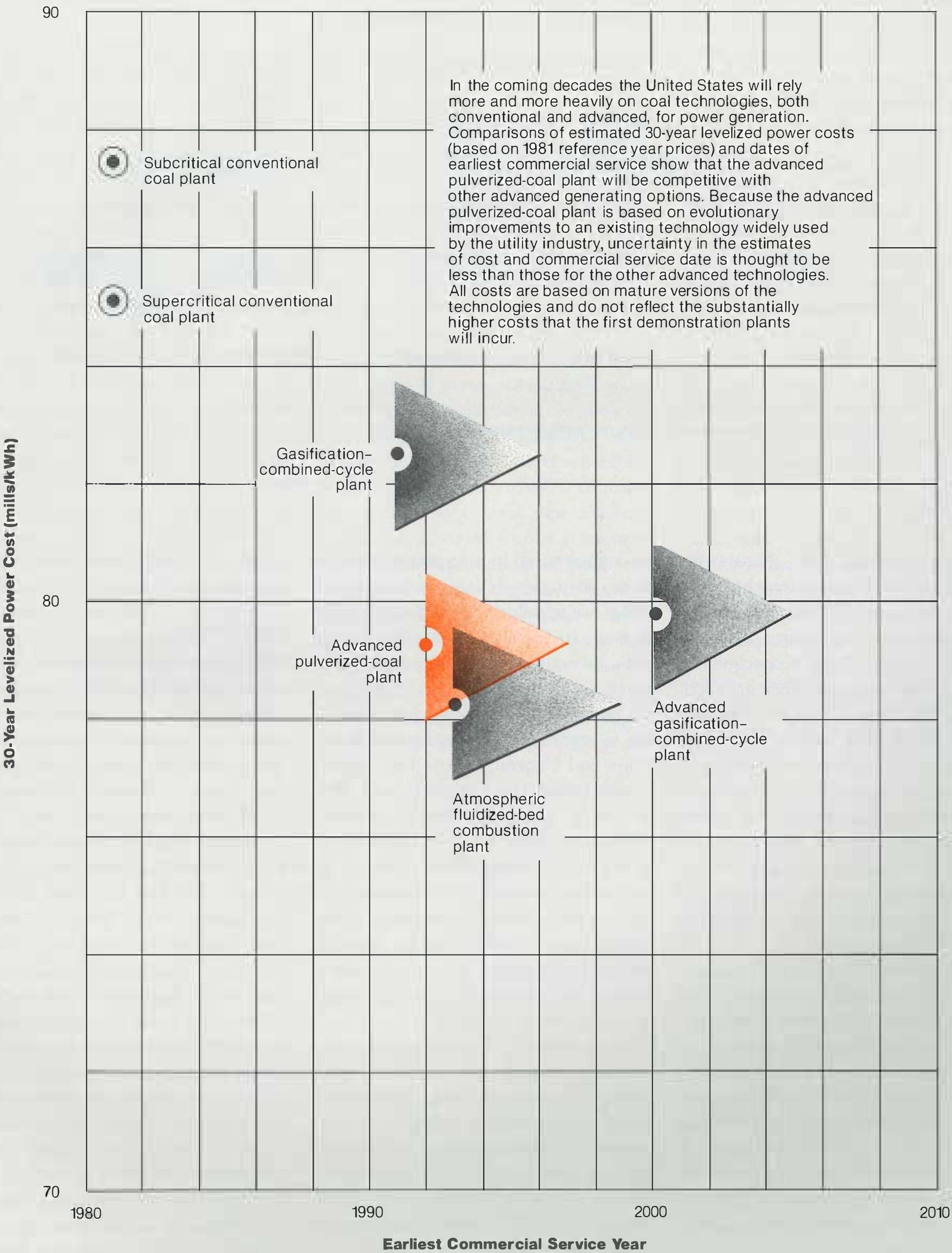
An important reason for EPRI's involvement in this area is the determination of the near-term and ultimate performance potential for conventional pulverized-coal plants. This is required both to establish a goal for performance and to stand as a measure against which the relative costs and benefits of other advanced coal-based options can be judged.

"What we in the industry typically have been doing up to now," says Giovanni, "is comparing the new, advanced-option technologies with a base, conventional plant that for all intents and purposes was technically frozen 20 years ago. With these new technologies maybe 10 or 20 years off in the future, we've been working with a 40-year gap in technology. This work closes that gap."

However, while advances in pulverized-coal-fired plant performance show promise, questions remain in some quarters of the utility industry. This is primarily the result of experience in the 1960s and early 1970s when a number of new plants were built and failed to live up to expectations. These plants, too, represented an advance over conventional pulverized-coal plant technology.

Various factors contributed to this failure. The new plants represented a considerable leap in technology in terms of both size and sophistication. With capacities as large as 1300 MW and steam pressures and temperatures as high as 5000 psi (34.5 MPa) and 1200°F (649°C), they all but dwarfed conventional capacity, which averaged about 400 MW and operated with steam pressures and temperatures of about 2400 psi (16.5 MPa) and 1000°F (537°C). As they represented first-generation technology, they required substantial and extensive shakedown. In addition, many were built with operating and design limitations to keep capital costs down.

Installation of these earlier plants coincided with an avalanche of new environmental control regulations and widespread deterioration in the quality of coal as premium, easily accessible supplies ran out and secondary veins began to be tapped. Although these problems are commonly thought to have affected most heavily the reliability of the large, supercritical units, this is not the case. New subcritical power plants installed in the same period showed similar reduced availability. As a cumulative result of these factors, plant performance in some instances was so poor that many utilities experienced considerable downtime and


90
80
70
1980
1990
2000
2010
30-Year Levelized Power Cost (mills/kWh)
Earliest Commercial Service Year
Subcritical conventional coal plant
Supercritical conventional coal plant
Gasification-combined-cycle plant
Advanced pulverized-coal plant
Atmospheric fluidized-bed combustion plant
Advanced gasification-combined-cycle plant
In the coming decades the United States will rely more and more heavily on coal technologies, both conventional and advanced, for power generation. Comparisons of estimated 30-year levelized power costs (based on 1981 reference year prices) and dates of earliest commercial service show that the advanced pulverized-coal plant will be competitive with other advanced generating options. Because the advanced pulverized-coal plant is based on evolutionary improvements to an existing technology widely used by the utility industry, uncertainty in the estimates of cost and commercial service date is thought to be less than those for the other advanced technologies. All costs are based on mature versions of the technologies and do not reflect the substantially higher costs that the first demonstration plants will incur.

COMPARISON OF PLANT CHARACTERISTICS

	Commercially Available Plants		Advanced Designs	
	Typical Subcritical	Best of Current Practice	Team 1 Design	Team 2 Design
Steam pressure	2400 psi (16.5 MPa)	3500 psi (24.1 MPa)	4500 psi (31 MPa)	4500 psi (31 MPa)
Steam throttle temperature	1000°F (538°C)	1000°F (538°C)	1100°F (593°C)	1050°F (566°C)
Steam reheat temperature	1000°F (538°C)	1025°F (552°C) and 1050°F (566°C)	1050°F (566°C) and 1050°F (566°C)	1075°F (579°C) and 1100°F (593°C)
Station net heat rate*	10,000 Btu/kWh	9300 Btu/kWh	8425 Btu/kWh	8875 Btu/kWh
Net power output	100–800 MW	400–1200 MW	400–1200 MW	400–1200 MW

*Environmental controls include flue gas desulfurization, electrostatic precipitator, and wet-cooling tower.

significant financial loss. Across the board there was a rapid retrenchment to smaller-size plants and subcritical steam conditions on the assumption that they would be more reliable. Consequently, the theory that improved efficiency sacrifices reliability became a rule of thumb.

What is different today is that plant managers and operators are learning to cope with and compensate for environmental controls and variable coal quality. More fundamental, the technology has matured as increasing coal costs, frustration in developing nuclear capacity, and the realization that higher efficiencies were possible took hold.

"In this new environment I believe the mood among utilities is changing," says Anthony Armor, EPRI project manager. "It used to be: 'Reliability is the only significant issue.' Now I believe it is: 'We need to do something about efficiency as a complement to the work we're doing on reliability.' In a sense, the pendulum is swinging from the extreme toward a balance. There is still a 'show-me' attitude, but efficiency has now become more of an important consideration."

Adds Giovanni, "Reliability need not be compromised in incorporating any of these advances. Indeed, some of the things we're talking about doing should improve it. Efficiency and reliability are not only not in conflict, they can be very much in lockstep."

Operating data support this. According to reports by Westinghouse Electric Corp. and General Electric Co., "In the range of plant sizes from 600 to 825 MW, in recent years supercritical double-reheat units have achieved availabilities of 80% on the average. This is higher than the average availability of 600–825-MW units as a whole and is comparable to the average availability of smaller units. If the technology base is in place—and it is—high availability and high technology are not mutually exclusive."

Although the U.S. utility industry has remained cautious, utility and manufacturing companies in Japan and Europe are more aggressive in opting for the advantages of supercritical plants. In addition, the Japanese have independently embarked on a development effort similar to EPRI's. Their development target for an advanced pulverized-coal plant is a 5000-psi (34.5-MPa) supercritical plant at 1200°F (649°C) and a double reheat of 1100°F (593°C).

Study teams

EPRI's study of the advanced plant involved two independent research teams, each consisting of a turbine generator manufacturer, a boiler manufacturer, an architect-engineer, and one or more utilities. Team 1 included Westinghouse, Combustion Engineering, Inc., Gilbert Associates, Inc., and Philadelphia Electric Co.; team 2 included General Electric, Babcock & Wilcox Co., Stone & Webster Engineering Corp., Boston Edison Co., New England Gas and Electric Association (now Commonwealth Energy System), and Jacksonville Electric Authority.

The base plant for both teams was essentially the same (i.e., the best-performance plant currently available commercially) and it was against this benchmark (not the 1950s vintage plant commonly referenced by similar studies) that improvements in technology were devised. Key recommended changes in this base plant included variations in the type of turbine, in boiler auxiliaries, feedstock equipment, and flue gas heat recovery.

Both teams recommended that development of the advanced plant should be pursued.

In the final reports, steam pressures were envisioned at about 4500 psi (34.5 MPa) with temperatures at about 1100°F (590°C). This compares to conventional practice of 2400–3500 psi (16.5–24.1 MPa) and 1000°F (538°C), respectively. Thermodynamic cycles with two steam reheat loops (rather than one) and additional feedwater heating at higher pressures were settled on. Turbines and boilers were also addressed and sliding pressure operation through the steam critical pressure point was recommended. In this manner, good performance can be maintained at partial loads to provide the necessary load-following rate. In another area, high nickel-chrome alloys were recommended for use in critical stress and corrosion regions to realize reliable long-term operation of the boiler, turbine, and steam auxiliaries.

Additional performance benefits were expected to accrue from low-temperature heat exchangers, more efficient fans and fan drives, and reduction of parasitic environmental control loads through operational integration of air, water, thermal, and solid-waste subsystems.

Reliability as good as the best current practice was a project requirement for the advanced pulverized-coal plant. This would be achieved by careful equipment design, improved materials, component and subassembly pretesting, and adequate design margins for the expected operating conditions. Further enhancement was anticipated by the effective use of redundant components, by designing the plant for easy maintenance, by comprehensive spare-parts practices, and by on-line diagnostic monitoring techniques.

The materials and design capabilities to accomplish these goals and to build these kinds of plants are available today. However, with operation at the pressures and temperatures envisioned, stress fatigue, creep rupture, and the like could become even more complex concerns, and verification of candidate materials and design is required prior to commercialization. Minor redesign of basic components and modifications to existing equipment for operation under supercritical conditions are needed as well. In boilers, for instance, some tube materials must be improved. And in turbines, advanced cooling methods for highly stressed rotating components can be used, as can improved materials for piping, valves, and nozzle boxes, and—with more-advanced concepts—for turbine rotor forgings.

Aside from these technological challenges, the advanced plant must demonstrate its economic superiority. Two factors mitigate this concern, however: Coal costs will undoubtedly increase substantially, putting an additional premium on improved efficiency. Because the advanced concept incorporates a whole range of improvements in design and materials, improvements that can be applied incrementally according to the economics of the day or of a particular situation, utilities can commit themselves piecemeal, as circumstances dictate, rather than in one lump sum.

"As fuel costs continue to increase in real terms, more and more of these improvements can be brought to bear," comments Yeager. "What we here at EPRI are charged with is ensuring that as these improvements are required, they are qualified and can be confidently made available to the industry." ■

This article was written by William Nesbit, science writer. Technical information was provided by Dan Giovanni and Anthony Armor, Coal Combustion Systems Division.

ON-LINE INFORMATION

Access to EPRI's R&D information data base helps reduce duplication of research activities and assists in broadening the use of new and improved technology throughout the electric utility industry.

Questions on energy technology R&D often crop up in the day of an electric utility staff member. For example, What are the current facts on electric power generation from biomass, particularly agricultural waste? What data are available on turbine corrosion? What research has been done on the type of pressurizers that malfunctioned on the TMI Unit 2 reactor? Many of these queries are passed along to EPRI.

Such referral is as it should be; EPRI has much to offer member utilities and others in terms of R&D information, and answers are readily found in EPRI's computerized Electric Power Database–R&D Information System (EPD–RDIS), developed and maintained by the Technical Information Division.

This on-line route to wider and quicker application of R&D results will be greatly enhanced by the recent availability of the EPD–RDIS on three major information-retrieval services: DOE's RECON, System Development Corp.'s ORBIT, and Lockheed's DIALOG.

Because most utilities have the terminals necessary to access these computerized data bases (even a TWX machine will do), no additional equipment is needed, and costs are quite modest considering the convenience. Unlike previous access to the EPD–RDIS, there are no longer any subscription fees, minimum monthly fees, or minimum search costs. (The average search will probably cost between $5 and $10.)

Any utility staff member can search EPD–RDIS after a few hours of instruction or study of the operating commands. When these commands are entered in the interactive terminal, the system responds by typing out R&D project records under any term or combination of terms selected by the searcher. For the first question above, the searcher could find references to biomass research by simply entering the term *biomass*. A more complete search would also include additional search terms. For example, suppose the command was to find all references that have either the term *biomass* or *agriculture* and one of the terms *waste utilization* or *solid wastes* or *waste-derived fuels* or *wood wastes* or *solid-waste power generation*. Within three minutes (most of it for typing the commands) the system will have found 38 citations on biomass and an additional 18 on the terms for agricultural wastes. These can be typed out on the terminal immediately, or they can be printed and mailed to the searcher. The total cost of the search would be approximately $7.50 if the citations are typed online or less than $5.00 if printed and mailed. Either way is less expensive than doing an equivalent search manually.

Besides receiving information quickly and with precision, the searcher is also assured that it is up-to-date because the data base receives changes on a monthly basis.

In addition to the details of EPRI research and that of about 120 utilities, the data base includes information on projects run by the Nuclear Safety Analysis Center and a number of owners groups: the Utility Water Act Group (which jointly sponsors research with Edison Electric Institute and EPRI), the Boiling Water Reactor Owners Group, the Steam Generator Owners Group, and the Relief Valve Program.

Information on each research project includes sponsor(s), project title, research correspondent, contractor, funding, and a list of publications that have resulted from the project. In addition, a technical abstract of the research objective is entered for each project funded for more than $15,000. Users of the data base may extract information by utility project number, Federal Energy Regulatory Commission category, EPRI subject category, reporting utility, prime contractor, cosponsors, and subject descriptors, as well as by a full text search with any combination of words from the descriptors, title, or abstract.

Contribution of data by utilities and others is purely voluntary, except in the case of the New York State utilities. Following a requirement of the New York State Public Service Commission, all New York utility R&D data are reported to the EPD–RDIS. The California State Energy Research, Conservation, and Development Commission also sends all state R&D project data to EPRI for inclusion in the data base.

Although the data base was established in 1974, some of the records it contains date back to the late 1960s. EPRI member utilities asked that the early research records be retained because the results of these projects are still of value to the utilities.

The reference book *Digest of Current Research in the Electric Utility Industry* is photocomposed from the data base and issued annually. It is sent to member utilities and other contributors of R&D data. Another publication, *Research and Development Projects*, which is brought up-to-date three times a year, presents objectives of current projects funded by EPRI and highlights special tasks or phases of work. Major contractors and cosponsors are named, and published reports are listed. These EPRI reports may be ordered from Research Reports Center and will soon be available for on-line ordering as well.

The Technical Information Division at EPRI, which builds the data base, can assist inquirers to obtain on-line access to EPD–RDIS or help with formulating inquirers' searches. The division is planning a series of workshops later this fall to help the utilities keep current with the evolving methods of retrieving EPRI information efficiently and effectively. Information on the locations and dates of the workshops or answers to any other questions on gathering information can be obtained from the Technical Information Division. ■

This article was written by Jenny Hopkinson. Background information was provided by Kenton Andrews, Technical Information Division.

Investing in Energy R&D

Will the private sector fund energy R&D programs deleted from the federal budget? A recent congressional hearing examined this question.

With all the changes of the new administration—new faces in new positions, new economic policies, and new power struggles—there is a new focus on the government's role in energy R&D. Early in its tenure, the Reagan administration announced that it planned "to restructure the technology programs of the Department of Energy to emphasize longer-term, high-risk, potentially high-payoff R&D, while terminating large technical demonstrations." The administration also stated that although it believes federal support for energy research is appropriate, the funding of large commercial demonstration plants should be left to the private sector.

A part of the administration's policy is to use tax incentives and the decontrol of oil and gas, which will result in higher fuel prices, to motivate private corporations to pick up the R&D projects no longer funded by the federal government, particularly those projects in the demonstration phase. But the success of this policy hinges on the answer to one question: Will the private sector pick up the energy R&D projects that are excluded from the federal budget? According to the testimony given at a recent congressional hearing, the answer—although qualified—is often no.

Representative Don Fuqua, chairman of the Energy Development and Applications Subcommittee of the House Science and Technology Committee, held a hearing on July 15 at which the issues of energy decontrol and tax incentives were discussed. Among the witnesses at the hearing was Milton Klein, senior assistant to EPRI's president.

Klein discussed how the shift in government R&D spending will affect EPRI's programs. Emphasizing that EPRI has carefully coordinated its programs with the energy R&D programs of the federal government in order to avoid duplication, Klein explained that EPRI and DOE have had a productive relationship in the joint support of large projects. "Thus, any change in federal energy R&D programs can have a major impact on our work. Such is the case with the reorientation brought about by the new administration," Klein testified.

Klein also discussed the ability of private companies—particularly utilities—to invest in energy R&D. He explained that basic to the administration's approach is the existence of a financially strong, free-market industry. "The electric utility industry is a financially stressed, regulated industry. It therefore differs significantly from other energy industries. It is having considerable difficulty undertaking even those investments needed to provide continuing, reliable service. It is less able to undertake the risks inherent in the development and proving out of new technologies. Despite this difficulty, the industry has continued its strong support of EPRI."

He also told the congressmen the long lead time for development and commercialization of many of the electricity-related technologies makes it difficult for the private sector to justify the investment risk. Klein emphasized that the lack of government support "reaches the most critical proportions when it becomes necessary to build large-scale demonstrations, which are essential elements in proving the economics and technical aspects of some of the new technologies. It must be emphasized that it is often necessary to gain experience with several large-scale projects before the risks are reduced to the level of an acceptable business risk. Thus, there are a number of programs foreseen during the next few years for which the funding mechanism is not evident." But he also commented that EPRI agrees with the approach taken by the new administration that places responsibility for developments on the private sector to the maximum possible extent.

Investment Risks

In basic agreement with EPRI that the private sector should share in the burden of research on new technologies, Sam Iacobellis, president of Rockwell International Corp.'s Energy Systems Group, and George Mechlin, vice president for research and development at Westinghouse Electric Corp., testified before the subcommittee as representatives of private industry. However, both Iacobellis and Mechlin were quick to point out that a private company's main concern is return on investment. It is doubtful, therefore, that the private sector will pick up any energy R&D projects that do not appear to be easily commercialized.

As Iacobellis told the subcommittee, "Although in basic agreement with the fundamental aspects of the new administration's energy R&D policies, we are still concerned that there may be an inconsistency in their implementation. It is our belief that the transfer of funds to the Synthetic Fuels Corp. and the general budget reductions are forcing DOE to withdraw from many potential high-payoff programs long before the appropriate point at which it is practicable for private industry to participate."

He went on to say that the market for major energy products is strongly influenced by government policies, particularly in the areas of regulatory matters, price controls, and tax credits. Because these government policies are beyond the control of industry and may vary over the life of a product, many companies find certain energy projects too risky. "Government policies related to Clean Air Act provisions, energy tax credits, the Fuel Use Act, PURPA provisions, oil and gas price decontrol, and nuclear regulations have been key market drivers in many of our own business areas," Iacobellis stated. "The development of a major energy product can take from 10 to 20 or more years from the inception of the concept to commercialization. As such, any industrial R&D on a promising product can be virtually wiped out by changes in government policies."

As both Klein and Iacobellis mentioned, the other aspect of the risk of many of these energy R&D projects is the long lead time for development, which may require enormous economic investments. Mechlin pointed out that R&D is a small part of the overall product life-cycle implementation, but it is an up-front cost. "With money borrowed at the prime rate of 20%, at least $33 in profit must be guaranteed by the year 2000 to motivate a $1 investment in energy R&D today. A 30% probability of success for the entire product cycle would reduce today's allowable investment to 30¢. Such logic must limit private sector energy R&D investment to a few low-risk, short-term projects."

Iacobellis reiterated this point, stating that large initial investments are required to conduct some energy projects; for example, a synfuel pilot plant can cost \$2–\$3 hundred million and the next phase of demonstration can cost up to \$2–\$3 billion. "In our opinion, some government agencies have not adequately understood the basic requirements of private industry to earn a reasonable return on investment in order to stay in business." He believes the government should support R&D for these large systems through the commercial demonstration phase of the projects.

Decline in Productivity

The prevailing mood of the hearing was that without continued federal funding for energy R&D, the amount of R&D performed in the country would decline. Coupled with a decline in R&D would be a decline in U.S. economic productivity. Stuart Eizenstat, formerly domestic policy adviser to President Carter and now in private law practice, explained that current investments in R&D by the private sector are not at the levels they should be. Eizenstat quoted the 1980 *Harvard Business Review,* which reported a steady decline in private sector R&D investment in recent years with little sign of change for the future. He went on to comment, "As this subcommittee pointed out in its charter for these hearings, American R&D as a percentage of GNP declined from 3% in 1964 to 2.2% in 1979, while Japan's percentage of GNP increased from 1.5% to 1.9% and Germany's from 1.6% to 2.3%. Although the precise causes of our declining productivity growth remain a mystery, many experts agree that increasing R&D would help improve industrial productivity."

Eizenstat also believes that contrary to the administration's policy, oil and gas decontrol alone are not sufficient to encourage private sector development of energy R&D, specifically the development of synfuels. But Eizenstat does believe that synfuels offer an excellent alternative to crude oil. He explained that the Synthetic Fuels Corp. was created to take some of the risk out of private sector efforts to develop synfuels from oil shale, coal, and crops because there are very few private companies that can invest \$2 billion in an untested synthetic process. "If we leave synthetic fuel to the operation of oil decontrol alone, we will likely be in the same position several decades from now as we have been since World War II, when synthetic technology became available—namely, without a viable synthetic industry."

Charls E. Walker, an economist and chairman of Charls E. Walker Associates, explained that although the decontrol of energy prices is the first step in an effective energy policy, it is not in and of itself an energy policy. He finds this to be particularly true in the U.S. economy, where energy prices have been controlled in the past and which is still suffering the consequences of rapid increases in imported oil prices. Walker told the subcommittee that changes are also necessary in federal regulatory standards, in regulations that inhibit competition, in patent policy, and in federal expenditures on R&D. All these changes "can have small but measurable influences on productivity."

Walker also pointed out that "unless the benefits of policy changes are transformed into improved and expanded capital stock, there will be little measurable change in U.S. productivity. It is here that changes in tax policy can be of special significance."

Federal tax incentives for companies in energy R&D can provide a bridge from a position of energy vulnerability to one of independence, Walker stated, and he favors an accelerated cost recovery system so that business will step up the rate of new productive investment. He also feels that the government should enact a broadly applicable, targeted incentive for R&D expenditures. "In the short run, the benefits in terms of improved productivity and employment growth are likely to be much greater from more rapid capital recovery than from tax incentives for R&D. It is clear, however, that tax policies for stimulating plant and equipment investment and for encouraging industry-funded R&D are complementary. Faster capital recovery will increase technical knowledge and encourage additional expenditures on R&D." Walker concluded that the government should accelerate R&D in the energy field as part of an overall national strategy to develop strategic independence.

Eizenstat agreed. "The substance of my message is that while oil and natural gas decontrol are critically important, this subcommittee and the full Committee on Science and Technology should maintain adequate levels of funding for energy R&D programs and should maintain and expand tax and other incentives for the development of alternative sources of energy and to encourage conservation."

EPRI's Programs

How the budget cuts will specifically affect EPRI's programs was outlined by Klein for the congressmen. As he explained in his testimony, "It has been necessary to slow the growth in EPRI programs at the same time as the federal government has cut back its direct support of electricity-related R&D."

Klein emphasized those EPRI programs that involve particularly close interaction with DOE. For example, EPRI is a major cofunder with the federal government, United Technologies Corp., and a group of utilities in the demonstration of a 4.8-MW fuel cell in Manhattan early next year. "The administration's original budget deleted funding to continue the test of the 4.8-MW fuel cell and directed funding to much longer-range second- and third-generation technologies."

Commenting that EPRI's resources alone are inadequate to complete the technical development and commercial introduction of the fuel cell, Klein stated that it now appears that both the House and the Senate have returned funds to the DOE budget for this project.

Two other large projects affected by the change in federal R&D programs include the construction of a 45-MW (e) demonstration of a binary-cycle geothermal power plant (the Heber plant near Bakersfield, California) and the initiation of a 100-MW demonstration of an integrated gasification–combined-cycle power plant at Southern California Edison Co.'s Cool Water station.

With cofunding from DOE, EPRI, San Diego Gas & Electric Co., and a number of other utilities, the Heber geothermal project would demonstrate the practicality of using hot water geothermal resources, which have the potential of producing 20–30 GW of power. The administration deleted funds for the Heber project from the DOE budget, but energy committees in both houses of Congress have included provisions for its continued funding in their respective FY82 DOE authorization bills.

Because of the administration's redirection of federal funds, the Cool Water project, supported currently by EPRI, Texaco, Inc., Southern California Edison, the Bechtel Group, Inc., and General Electric Co., may have to turn to the Synthetic Fuels Corp. for government support. The sponsors of the project have already submitted a proposal to SFC for $75 million to complete the project funding, yet as Klein told the subcommittee members, "the likely delay before the Synthetic Fuels Corp. considers the proposal poses a considerable problem for the project." The delay is compounded by the fact that at the time of the hearing, only the chairman of SFC, Edward Noble, had been confirmed, and SFC cannot act until the remaining members of the board are appointed.

Other EPRI programs affected by the redirection of federal funds include a coordinated effort in the R&D of electric energy systems to improve the efficiency and reliability of electricity generation, transmission, and distribution; R&D in fluidized-bed combustion; and the development of advanced batteries for energy storage. This last effort has included the construction of the Battery Energy Storage Test (BEST) Facility, which was dedicated recently in Hillsborough Township, New Jersey. "Although the facility construction has been completed, we are concerned as to whether DOE's 50% funding share for equipping the facility will be available, and we are also concerned that its advanced battery program be brought to the next stage of validation, which involves the testing of full-scale battery systems in the facility," Klein told the congressmen.

Recommendations and Proposals

The consensus of the witnesses testifying before the subcommittee was that continued federal support of energy R&D is essential if the nation is ever to gain energy self-sufficiency. Not only is the federal funding of R&D required but also the decontrol of both oil and natural gas, development of a synthetic fuels industry, increased tax incentives for private sector involvement in R&D, and financial help for the electric utility industry. It is not a question of relying on any one of these, but all options must be made available to increase the development of new energy technologies. As Iacobellis stated in his testimony, "We believe appropriate government R&D spending in the energy area will be paid back many times over in terms of reduced vulnerability to OPEC monopoly pricing and increased national security."

The congressmen concurred with the recommendations of the witnesses to support all avenues to increased R&D spending. As Representative Harold Volkmer mentioned during the hearing, the new administration's proposal to fund only long-term, high-risk projects is confusing in terms of defining its objectives. Does the administration mean that there are actually two definitions: long-term projects and high-risk projects or is funding only available for projects that are both long-term and high-risk? Volkmer added, "Some projects are bound to fall through the cracks of such a plan. For example, if the government had not funded the breeder reactor, the technology would never have been developed."

General congressional support for more energy R&D also appears to be increasing. Representative Hamilton Fish, ranking Republican on the subcommittee, has sponsored a bill in the House that provides a 20% investment tax credit for the capital costs of private sector energy R&D activities. This proposed legislation, the Energy Research and Development Tax Incentives Act of 1981, would cover activities relating to the development of fossil, solar, geothermal, and other energy resources and energy conservation.

"R&D has been one of the primary bases on which our nation has attained its world economic leadership," Fish stated. "We need to provide strong federal support if our nation is to maintain an effective energy research program. I believe that an investment tax credit for private energy R&D is vital if our nation is to continue to pursue the development of high-payoff energy technologies that will allow us to develop and utilize our energy resources in a more efficient manner." ■

This article was written by Christine Lawrence, Washington Office.

Coal-Cleaning Facility Gears Up

Systems developed at the new facility will promote less expensive, more efficient electricity generation from a wide range of domestic coals.

Situated near Homer City, Pennsylvania, EPRI's Coal Cleaning Test Facility (CCTF) is gearing up to begin operation early in 1982. The facility has been undergoing final acceptance testing, which is expected to be completed this month. CCTF was authorized in 1978, and it is this country's newest and most advanced facility for coal-cleaning research, development, and demonstration.

Based on commercial-scale equipment, CCTF has a nominal design feed capacity of 20 tons per hour of fine coal and the ability to simulate a large number of commercial fine-coal-cleaning flow sheets. Cleaning operations that can be evaluated at the facility include heavy-media cycloning, water-only cycloning, tabling, and froth flotation. Fine-coal and refuse dewatering can be accomplished by one of two processes—centrifugation or filtration.

The facility's first task is expected to be a characterization of the cleanability of eight different coals from the nation's major steam-coal producing regions. Participating utilities will deliver run-of-mine coal samples of approximately 1000 tons to CCTF, along with detailed information on the source and mining procedure for each sample.

Other major CCTF program objectives include developing the engineering data required for optimal commercial cleaning plant design; accelerating the use of improved cleaning equipment, flow sheets, and instrumentation in commercial coal-cleaning plants; demonstrating improved coal sampling and analytic procedures; developing and maintaining a utility-oriented national coal quality data base; and providing training for coal preparation engineers and coal-cleaning plant operators.

In addition to EPRI, CCTF is being sponsored by Pennsylvania Electric Co. (a subsidiary of GPU Service Corp.), New York State Electric & Gas Corp., and the Empire State Electric Energy Research Corp. To provide planning guidance, an industry advisory group has been established for CCTF. The operations contractor is Kaiser Engineers, Inc. ■

Meeting on Geothermal Energy

A recent gathering of about 130 geothermal experts emphasized the high national and international interest in geothermal energy as an electricity source. The 130 were participants in the Fifth Annual EPRI Geothermal Conference, held June 23–25 in San Diego, California. The three-day meeting promoted information exchange on all facets of geothermal development in the United States and in seven other countries.

According to Vasel Roberts, program manager, Geothermal Power Systems, the conference confirmed that geothermal energy can become an important source of electricity generation in the future. Utility projections presented at the meeting showed that by the year 2000, some 30 utilities plan to have some geothermal capacity and throughout the

United States, some 11 GW of power is expected from geothermal. (EPRI has projected geothermal-derived electricity capacity will reach 16 GW by 2000.)

In addition to announcing plans to expand geothermal generating capacity, presentations at the meeting showed that many utilities will likely incorporate EPRI-developed technologies into their geothermal facilities. Development of a hydrogen sulfide removal system, computer codes for simulation of scale buildup, and detailed plant design studies are among the EPRI efforts that will be applied by the expanding geothermal industry in this country. ■

Video Memo Introduced

EPRI has recently started a new technology information service for utility executives, planners, and engineers. Known as *Video Memo*, the service consists of a series of videotapes to be distributed monthly. Each 15- to 20-minute tape covers a different technology, topic, or issue. The focus may be a state-of-the-art review, a summary of important research results, or an overview of an entire EPRI program area.

Two of the tapes are now available. The first, "Fuel Cells: A Progress Report," is a panel discussion featuring participants from EPRI, Consolidated Edison Co., Pacific Gas and Electric Co., and the Santa Clara Electric Department. The second, "The Fabric Filter Baghouse," was shot on location at the Arapahoe Emissions Control and Test Facility in Colorado. Future topics include: technology applications, Electrical Systems Division research, EPRI's Nondestructive Evaluation Center, power plant performance and reliability, and rate design.

The *Video Memo* series is distributed free to EPRI members. Additional copies will be provided at duplication cost. ■

CALENDAR

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

SEPTEMBER

9–11
Workshop: Modeling of Cooling-Tower Plumes
Chicago, Illinois
Contact: John Bartz (415) 855-2851

17–18
Seminar: Compressed-Air Energy Storage (CAES)
Chicago, Illinois
Contact: Robert Schainker (415) 855-2549

17–18
Symposium: Underground Cable Thermal Backfill
Toronto, Ontario
Contact: T. Rodenbaugh (415) 855-2306
S. Boggs (416) 231-4111

21–25
Workshop: Zero Discharge
Steamboat Springs, Colorado
Contact: Roger Jorden (303) 824-4411
Winston Chow (415) 855-2868

23
Seminar: Thermal Energy Storage for Cooling Commercial Buildings
Washington, DC
Contact: D. Dougherty (202) 872-3317
C. Cross (415) 855-2432

30–October 2
Review and Workshop: 1981 Solar Program
St. Paul, Minnesota
Contact: E. A. DeMeo (415) 855-2159

OCTOBER

2
EPRI Sulfate Regional Experiment: Results and Implications
Dearborn, Michigan
Contact: Monta Zengerle (415) 855-2736

4–8
Environment and Nonnuclear Solid Wastes
Gatlinburg, Tennessee
Contact: Ishwar Murarka (415) 855-2150

14–16
International Symposium: Electrostatic Precipitation
Monterey, California
Contact: Dan Giovanni (415) 855-2442

14–16
Symposium: Power Plant Fans—The State of the Art
Indianapolis, Indiana
Contact: Kathy Davis (415) 854-2186

18–23
Water Chlorination: Environmental Impact and Health Effects
Pacific Grove, California
Contact: R. Kawaratani (415) 855-2969

20–22
Seminar: FGD Systems Data Book and Sludge Disposal Manual
Pittsburgh, Pennsylvania
Contact: Charles Dene (415) 855-2425

26–28
Workshop: Modeling the Performance of Cooling Towers
Chicago, Illinois
Contact: Hugh Reilly (415) 855-2469

NOVEMBER

4–5
Seminar: Prevention of Condenser Failures—The State of the Art
Arlington, Virginia
Contact: B. C. Syrett (415) 855-2956

18–20
Seminar: FGD Systems Data Book and Sludge Disposal Manual
Denver, Colorado
Contact: Charles Dene (415) 855-2425

DECEMBER

1–3
Seminar: PCBs
Dallas, Texas
Contact: Gilbert Addis (415) 855-2286

R&D Status Report
COAL COMBUSTION SYSTEMS DIVISION

Kurt Yeager, Director

HEAT REJECTION

*This report summarizes the R&D activities of EPRI's heat rejection subprogram, which focus on water-conserving cooling systems; cooling equipment specification, selection, and testing; and environmental impacts of cooling systems. It presents updated information on the status of efforts reported earlier (*EPRI Journal*, October 1980, p. 40) and highlights current project development.*

Water-conserving cooling systems

The principal EPRI effort in this area is the demonstration of advanced wet-dry cooling technology based on an ammonia phase-change heat rejection system (RP422). Construction of the 10-MW demonstration facility at Pacific Gas and Electric Co.'s Kern plant in Bakersfield, California, was completed in April on schedule and within budget (Figure 1). The test program was begun in August after the successful completion of acceptance test procedures.

On the basis of a comparison with commercially available water-conserving cooling systems, it is projected that use of the advanced technology could save the utility industry $20 billion by the year 2000. A utility group has been formed to provide practical advice to aid in commercialization, as well as financial support for additional project tasks of specific interest to its members. The group currently consists of PG&E, Southern California Edison Co., the Los Angeles Department of Water & Power, and the Canadian Electrical Association; additional participants are being sought. EPRI is also cooperating closely with Electricité de France, which is building a 20-MW ammonia-based binary-cycle facility in France that is scheduled to begin operation in January 1983.

A three-year operation and testing program will be conducted at Bakersfield under the direction of Battelle, Pacific Northwest Laboratories and with sponsorship from the utility group, DOE, and EPRI. The following EPRI reports present results to date on this

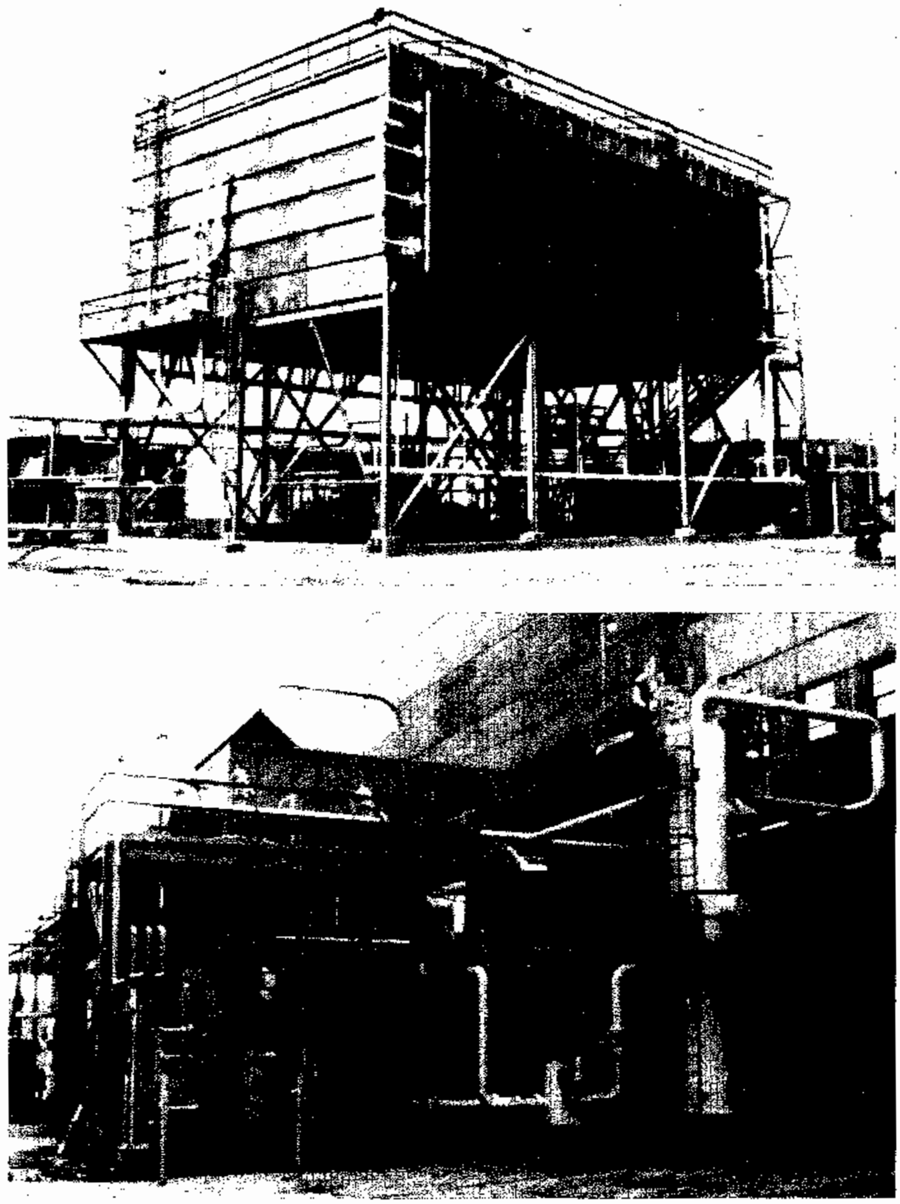


Figure 1 Testing is under way on an advanced wet-dry cooling technology at this 10-MW demonstration facility at Pacific Gas and Electric Co.'s Kern power plant near Bakersfield, California. Compared with commercially available water-conserving systems, this ammonia-based technology is projected to yield cost savings of up to 50%. Shown are the cooling tower (top) and the condenser-reboiler.

project: CS-1324-SY, CS-1530, CS-1668, CS-1915, and CS-1926.

In a companion project, Chicago Bridge and Iron Co. has designed a capacitive cooling system for inclusion in the test facility (RP1260-23). The system, which features a water tank that functions as a thermal capacitor, eliminates water consumption for cooling and operates in a zero discharge mode. It is economically comparable to the ammonia-based wet-dry cooling system.

The economics of various water-conserving cooling systems are being compared by R. D. Mitchell, consulting engineer, in another companion project (RP1260-21). This generic study covers the ammonia-based technology being developed under RP422, as well as both direct and indirect (closed-water-loop) cooling systems. Economic comparisons are being made among optimized systems over a broad range of power plant sizes, fuel costs, and water consumption. Results of the study, which will be completed this year, should aid utilities in selecting the optimal type of water-conserving cooling system for specific site conditions.

Equipment specification and evaluation

Two projects are being sponsored to provide the utility industry with the experimental data and predictive capability required for the proper specification and evaluation of wet cooling towers. In the first, CHAM of North America, Inc., has developed a computer code incorporating a mathematical model capable of predicting the thermal performance of mechanical- and natural-draft cooling towers of both counterflow and cross-flow design (RP1262). This code, VERA2D, has been validated by comparing its predictions with test data from existing cooling-tower installations. A typical application of VERA2D is illustrated in Figure 2, which presents the predicted relationship between cooling-tower fan power and the temperature of water leaving the tower. This information is useful in determining the potential for upgrading cooling-tower performance by increasing the airflow through the tower.

A workshop will be held October 26–28, 1981, in Chicago to present the completed computer code to the utility industry. The mathematical basis of the code will be discussed and its input and output features detailed. Workshop participants will have an opportunity to use VERA2D to evaluate specific cooling-tower performance problems.

The second project will involve the design, construction, and operation of a small-scale cooling-tower test facility (RP2113). Under a planning contract, Environmental Systems Corp. has identified key project elements, including potential utility cosponsors, utility host sites, and facility instrumentation and structural requirements (RP1260-22). The test facility will provide an economical means of developing detailed performance data on existing and proposed cooling-tower fill configurations. To investigate performance under actual operating conditions, several fill configurations will also be tested in a dedicated cell of a cooling tower at the host utility's site.

An effort to improve the ability to predict cooling-pond performance and evaporative loss is continuing at the Massachusetts Institute of Technology's Ralph Parsons Laboratory (RP1260-17). A workshop was held in September 1980 to identify promising field measurement techniques. In preparation for a field test program, a limited series of tests was conducted in June 1981 at a highly instrumented geothermal test pond to screen various advanced techniques of evaporation measurement. A workshop is scheduled for the end of the year to evaluate the results of the screening tests and to develop detailed plans for the field test program.

A project to develop field-validated analytic models for use in hydraulic transient design calculations for circulating-cooling-water systems is continuing at the Georgia Institute of Technology (RP1342). A final report, which will compare field test results with model predictions, is scheduled for publication in the fall of 1982.

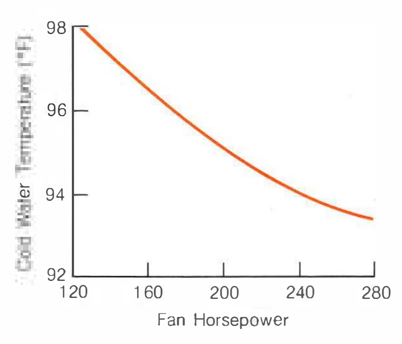


Figure 2 VERA2D, a computer code for simulating cooling-tower thermal performance, was used to predict the effect of fan horsepower on cold water temperature (i.e., the temperature of water returned from the cooling tower to the steam condenser) for a given heat load. These cooling-tower design conditions were assumed: a cooling range of 22.1°F (12.3°C), a wet-bulb temperature of 76.8°F (24.9°C), and a water flow rate of 18,200 gal/min (1.15 m^3/s).

Environmental impacts of cooling systems

Mathematical models of plume dispersion from cooling towers, both natural draft and induced draft, are being improved for utility use in research at Argonne National Laboratory (RP906). Research to date is presented in a comprehensive five-volume report (CS-1683); a summary report is also available (CS-1683-SY). A generalized model (with single-tower and clustered-tower submodels) has been developed to predict the seasonal and annual frequencies of visible plume impact, droplet drift, ground fogging, and icing of surrounding terrain. This work includes the development of methods to generate statistically reliable predictions of weather and tower operating conditions on the basis of data typically available to siting engineers. The overall objective is a flexible, reliable code for use in environmental impact and plant siting studies. A workshop this month in Chicago will present the current version of the code to the industry. Another workshop is scheduled for the fall of 1982 to transmit the final code and documentation.

Code development in the area of cooling-tower drift is being complemented by laboratory studies. A wind tunnel was constructed at MIT for use in evaluating various methods of plume droplet drift measurement against a calibrated reference method developed in this effort. The evaluation program is in progress (RP1260-11).

Projects are under way that focus on the entrainment and entrapment of aquatic species in once-through cooling systems and on changes in intake design to reduce these problems. A porous dike intake structure at New England Electric System's Brayton Point station has been tested by New England Power Service Co. and Marine Research, Inc. (RP1181). Results indicate that no serious clogging or fouling problems have occurred during the two years of system operation. EPRI plans to sponsor tests of other promising devices at Brayton Point and to participate in the testing of a full-scale porous dike that New England Electric System is considering installing at the station.

Another project development plan involves the evaluation of intake screening devices at sites with widely varying characteristics. This evaluation would be performed in connection with a clearinghouse on intake screens that EPRI is developing for the collection, analysis, and dissemination of biological data, information on operating experience and problems, and engineering and cost data.

In a related effort at Oak Ridge National Laboratory, a condenser simulator is being used in a series of entrainment mortality studies (RP1183). This work will be completed in 1981. *Subprogram Manager: John Bartz; Project Manager: Hugh Reilly*

COOLING-SYSTEM BIOFOULING CONTROL

*The research activities in EPRI's water quality control subprogram are divided into three major categories: water management, effluent control, and biofouling control. The first two were the topics of earlier R&D status reports (*EPRI Journal, *July/August 1979, p. 38, and July/August 1980, p. 32). This report reviews the results of completed projects and the status of ongoing work in biofouling control. A future* Journal *will carry a status update on projects in the other areas of the subprogram.*

A major problem in power plant cooling is biofouling—the deposition of organic material on cooling-system surfaces. The detrimental effects of biofouling are reduced heat transfer capability in condensers, increased pressure drop or lower flow, and accelerated corrosion. The mechanisms of biofouling are complex, involving biological, physical, and chemical interactions, and its proliferation is dependent on several factors: water quality, plant process conditions, interactions with other cooling-system fouling phenomena (e.g., scale deposition), and the control measures used.

EPRI is seeking to develop a systematic understanding of biofouling. Projects are under way or are being planned to develop data bases, to explore chlorine reduction techniques and alternatives to chlorination, and to develop design and operating guidelines. The ultimate goal of this research is a set of reference manuals that will integrate biofouling control with site selection, plant design, component selection, operation and maintenance procedures, instrumentation and control concepts, and regulatory and ecological concerns.

Forms of biofouling

A plant cooling system provides an ideal environment for biological colonization and growth. Two forms of biofouling are significant: microbial fouling of heat exchangers and macroinvertebrate fouling of intake and discharge channels.

One variety of microbial fouling is the formation of slime, a complex bacterial matrix with a filamentous surface and a viscoelastic substrate. An important factor in determining slime characteristics and growth rate is the quality of the source water—that is, the microbial energy, nutrients, and the silt, sand, and organic matter it contains. Several factors that govern slime accumulation and growth rates appear to be seasonal (e.g., water temperature and nutrient load), and accumulation is generally more rapid in the spring and summer than in the winter.

Slime films on power plant condenser tubes reduce heat transfer between the condensing steam and the cooling water, thus diminishing efficiency. A universal increase in turbine back pressure of only 0.1 inch of mercury (0.34 kPa) would cost the industry approximately $100 million per year. If unabated, the film will begin to constrict the cooling-water flow through the heat exchange tubes. Such severe fouling would force a plant to shut down for condenser cleaning and maintenance. In addition to cleaning costs, up to $800 a day per MW of generating capacity would be expended for replacement power.

A majority of U.S. power stations obtain their water supplies from surface streams, lakes, and oceans. As a result, these plants are exposed to yet another form of cooling-system biofouling: the colonization of macroinvertebrates, for example, mussels, barnacles, and clams (Figure 3). This fouling is usually most evident in the intake and discharge channels of the plant's cooling system. Over time the layered growth of macroinvertebrates can cause not only flow resistance but also blockage of the condenser tubes due to the release of detritus material.

Control methods and problems

Active and passive measures are available for biofouling control. The preferred conventional method is chlorination. Roughly 60% of all plants with once-through cooling systems add chlorine to their cooling water, and almost all plants with cooling towers use chlorine. In many years of research and operating experience, this approach has been found to be both effective and reliable. More data are available on chlorination than on any other biofouling control method. Nonetheless, only within the last five years has substantial effort been directed at developing models of how chlorine works.

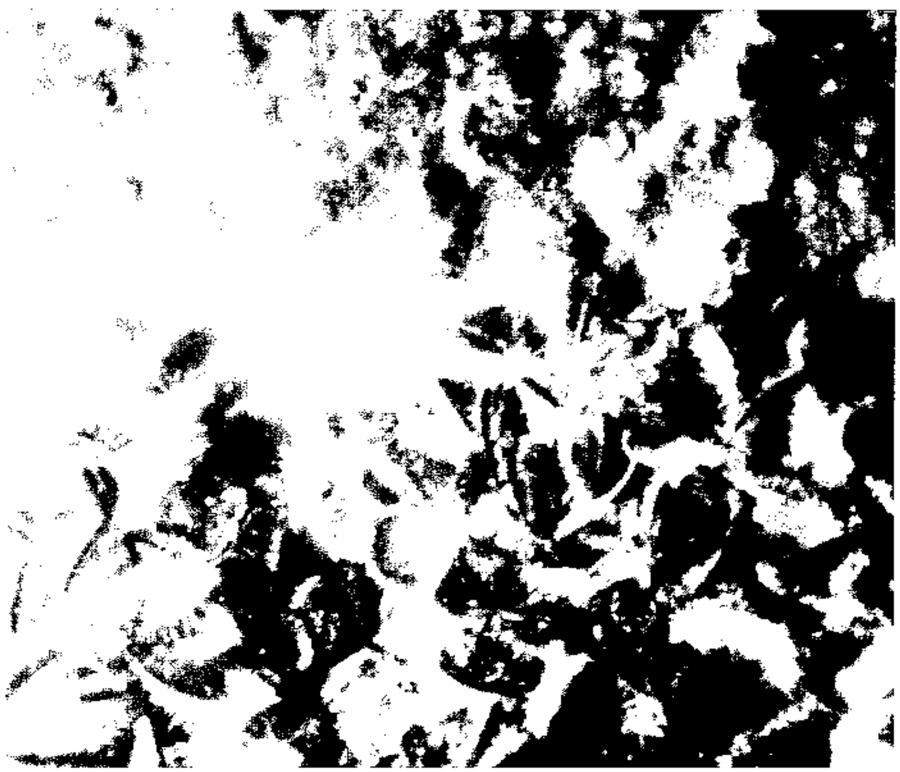


Figure 3 Macroinvertebrate colonization at the intake structure of Southern California Edison Co.'s San Onofre station, Unit 1. Shown here are layers of mussel and barnacle growth. The Asian clam is another macroinvertebrate found in some intake systems of power plants on the West Coast, in the Gulf states, and as far as the eastern seaboard.

Other chemical oxidants, biocides, and dispersants, many of them proprietary, are also available. Mechanical and thermal techniques, such as recirculating rubber balls, flow-directed brushes, and thermal-hydraulic shocks, can also provide on-line relief; these are primarily designed to prevent excessive slime formation on condenser tubes. A variety of mechanical-chemical off-line manual cleaning procedures are often employed as a last resort.

Passive measures include control of design-related factors that may affect the rate of biofouling, such as water velocity, condenser tube wall temperature, and condenser alloy and coating toxicity. Biofouling can also be passively mitigated by selecting source waters with high levels of suspended materials to scour the tubes.

The use of chlorine by utilities, other industries, and water treatment plants is widespread. Concern about the ecological impact of residual chlorine discharges led EPA to propose tighter controls. Under the revised effluent guidelines for steam-electric power plants proposed in October 1980, residual chlorine emissions would be drastically curtailed. A utility would have to demonstrate to EPA its need for chlorination, and at plants permitted to use chlorine, the concentration of total residual chlorine would not be allowed to exceed 0.14 mg per liter. Furthermore, discharge would be permitted for no more than two hours a day from a central station outfall. The same limit on chlorine discharge would also apply to stations with cooling towers.

This situation poses a real dilemma. Utilities are expected to refine their control procedures when little is known about the fundamental mechanisms of biofouling or its control, and when no means are available for accurately detecting the onset of condenser biofouling. Utility operators and designers urgently need information on microbial and macroinvertebrate fouling mechanisms; reliable methods or devices for rapid, on-line detection of biological activity and growth; and effective means of preventing or removing biological accumulation in power plant cooling systems. Several projects have been completed, and more are being planned, to meet these industry needs. As part of this effort, environmental impact investigations are being sponsored by EPRI's Environmental Assessment Department.

Utility biofouling experience

Information on the biofouling control experience of the utility industry is being collected and analyzed (RP1132). The initial phase of the project, which emphasized condenser tube microfouling in once-through cooling systems, has been completed and is reported in CS-1796.

In this phase NUS Corporation—with the cooperation of the Edison Electric Institute (EEI) and many utilities—conducted an industrywide survey on biofouling control practices at once-through cooling stations and reviewed existing data bases. To verify the data obtained, detailed interviews were conducted at 29 selected plants exhibiting a range of biofouling conditions. The resulting information was put into a computer format and added to the Atomic Industrial Forum Power Data Base. (EEI now operates this data base through Utility Data Institute, Inc.) Also as part of this study, hypotheses on the effect of water quality, condenser design and operating variables, and biocide dosage were developed and tested.

The survey revealed the following.

- Most plants have both macrobial and microbial fouling problems.
- Source-water characteristics, geographic location, seasonal variations, and condenser and plant design are all major influences in biofouling.
- Chlorine is normally an effective agent for controlling biofouling. Requirements range from none to quantities well in excess of allowable discharge limits. High levels of suspended solids are common at plants requiring no biocide.
- Opportunities for chlorine reduction appear to exist at many, but by no means all, plants.

The survey also found that biofouling practices are changing rapidly; thus available data are not always current and must be checked carefully for reliability.

The 29 plants selected for detailed study have a total of 98 units, 55 of which are cooled by brackish water or seawater and 43 by fresh water. Table 1 presents plant responses on the most significant condenser biofouling problem each faces and shows the distribution of the problems by plant cooling-water source. Regarding chlorination practices, 16 of the plants add chlorine gas to their cooling water, 7 add sodium hypochlorite, and 6 use no biocide. Two plants have installed dechlorination systems.

In a follow-on study, Lockheed Environmental Systems analyzed the Power Data Base on chlorination practices and condenser performance to identify areas in which further R&D efforts are required to supplement existing data (TPS80-739). Three major areas were identified. First, a reliable, sensitive device for the rapid measurement of condenser performance is needed to enable early detection of cooling-system biofouling and hence more effective and timely corrective action. Second, more data are needed on the reaction of biocides on the biofilm layer and their effectiveness in controlling biological growth. Third, toxicological studies of biocides other than chlorine are needed to resolve environmental impact issues. To avoid substituting one problem for another, the reactions and ecological effects of alternative biocides and their by-products must be well understood.

Biofilm development and control

Slime formation and control were thoroughly examined under laboratory conditions at Rice University (RP902). This work, which is reported in CS-1554, had three major objectives: to develop an understanding of, and a model for, the mechanisms of biofilm development and destruction; to determine the effectiveness of biofilm destruction by chemical oxidants, primarily chlorine; and to

Table 1
CONDENSER BIOFOULING SURVEY

Most Significant Fouling Problem	No. of Plants by Cooling-Water Source: River	Lake	Bay	Estuary	Ocean	Total
Debris	5	0	0	0	0	5
Microbial fouling	8	2	0	1	2	13
Macrobial fouling	0	0	3	3	2	8
No fouling	2	0	0	1	0	3

develop a practical, reliable, and sufficiently sensitive device for monitoring microbial fouling.

The laboratory slime films were found to be viscoelastic. In situ films were 95–98% water. The thermal conductivity of the films was essentially equal to that of water at the same temperature. Under stress, the slime was filamentous and pliable, with a maximum thickness of 100–500 μm (4–20 mils). Film development rate and thermal resistance depend on fluid velocity, nutrient concentration, and heat exchanger wall temperature. Films greater than 50 μm (2 mils) thick can be detected by measuring either water-side pressure drop or heat transfer efficiency loss. On the basis of the laboratory investigations, pressure drop seems to be the preferred indicator.

Film development consists of three stages: induction, growth, and plateau stages. Plotting biofilm thickness as a function of time results in a sigmoidal curve. During the induction stage and the early growth stage, changes in fluid frictional resistance (as determined by pressure drop measurements) and heat transfer resistance were barely evident. As the film continued to grow, significant increases in frictional resistance were observed; these were caused by film roughness. However, primarily because of increased convective heat transfer due to the roughness, heat transfer resistance was not as responsive to film growth. By the time a change in heat transfer resistance was detected, the plant condenser would have been severely affected and the fouling deposit difficult to remove.

Two devices, a tubular fouling reactor and an annular fouling reactor (which consists of a stationary outer cylinder and a rotating inner cylinder), were used to quantify fluid frictional resistance created by biofilms. Of all the biofilm measurement techniques investigated (volumetric displacement, determination of biofilm thickness by an optical microscope, biofilm mass measurement, heat transfer resistance measurement, and frictional resistance measurement), the annular fouling reactor frictional resistance technique was considered the most promising for sidestream use in an operating power plant. Although not field-evaluated, it was extremely reliable from an operations and maintenance standpoint, and its sensitivity was superior to that of other techniques.

Chemical oxidants, such as chlorine, ozone, and hydrogen peroxide, were found to be most effective in destroying biofilms when applied at high dosages for short durations. For example, tests indicated that three 5-min injections representing an average oxidant concentration of 1 mg per liter would be more effective than continuous addition for 30 min at 0.5 mg per liter. This approach, however, is contrary to effluent guidelines. If chlorine must be used to prevent condenser tube surface biofouling, continuous low-level chlorination may be an effective approach. Ozone performed well in cleaning fouled surfaces, whereas other oxidants always left residual film deposits.

Ozone treatment

While laboratory studies under RP902 have demonstrated the ability of ozone to remove biofilms completely from heat exchange surfaces, practical application in the utility industry requires detailed information on the economic and technical feasibility of ozone treatment as an alternative to chlorination. Among the questions to be answered are these: what dosages and injection procedures are appropriate, what design and operating problems are associated with applying ozone and installing ozone generation facilities at plants, what are the estimated costs for ozone treatment at a full-scale power plant, and how do these costs compare with chlorination costs?

To provide answers to these questions, EPRI and Public Service Electric and Gas Co. (New Jersey) are sponsoring a project that uses a mobile test facility with three pilot-scale condensers to simulate actual once-through condenser operations (RP733). In the first phase of this project, the facility was used in tests at PSE&G's Bergen generating station to develop comparative data on chlorine and ozone treatment. It proved to be capable of duplicating the operating characteristics of the main plant condensers, while allowing flexibility in measuring biofouling accumulation and evaluating control options.

The three test condensers were operated in parallel with each other and with the main plant condensers at Bergen (Figure 4). One test condenser used ozone and one chlorine; the third, which used no chemical treatment, served as the reference. By measuring the heat transfer coefficient across the test condenser tubes and/or the water-side pressure drop, minimum effective levels of chemical treatment were determined for each case. (The tests demonstrated water-side pressure drop to be as effective as heat transfer coefficients in reflecting fouling conditions inside the tubes. This finding supports the results of RP902.)

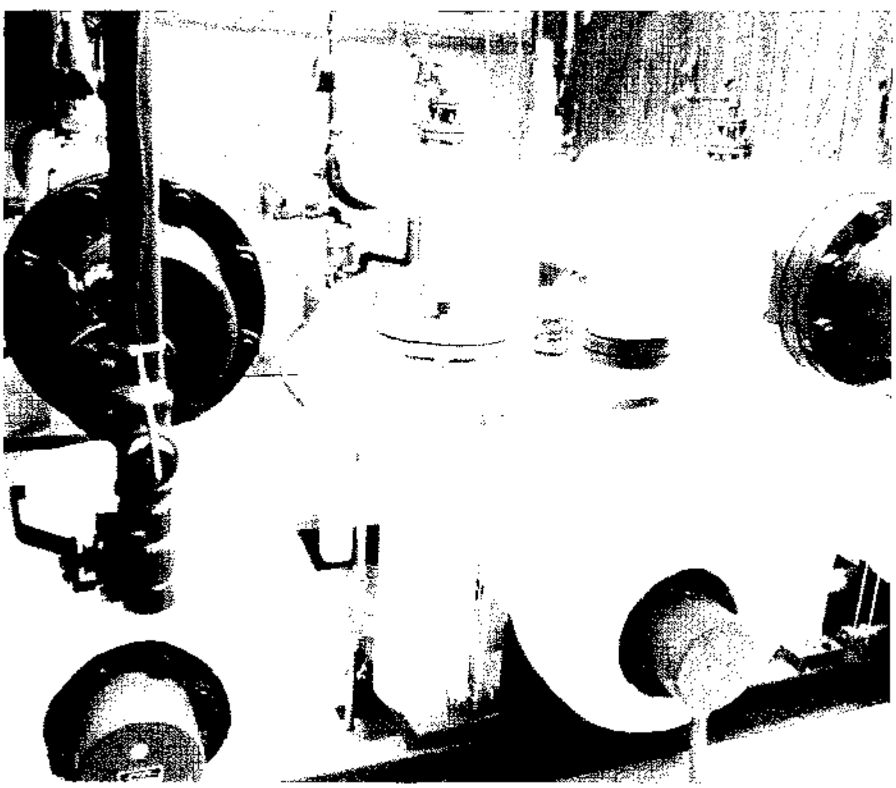


Figure 4 These pilot-scale condensers were used in tests at Public Service Electric and Gas Co.'s Bergen station to compare chlorine and ozone treatment methods for biofouling control.

The Bergen tests confirmed the feasibility of using ozone for condenser biofouling control at that site, but ozone was neither as effective nor as economical as chlorine. For instance, when applied for two hours a day, chlorine achieved effective biofouling control down to a dosage of 0.1 mg per liter. In contrast, an ozone dosage of 0.5 mg per liter was required for the same degree of control. It should be pointed out, however, that because water quality is site-specific, the character and growth of biological organisms, the biochemical reactions of biocides, and hence the efficiency of chemical treatments will vary from plant to plant. In terms of economics, an ozone generation system for Bergen would cost $3.3 million, compared with $0.5 million for a chlorination system; the daily operating costs of the ozone system were estimated to be 2.5 times the chlorination costs.

With the completion of the Bergen station testing, which is reported in CS-1629, the test facility is being upgraded and moved to a second site, PSE&G's Mercer station. In this phase, testing will be expanded to include chlorine reduction techniques. Once the testing program is completed, the long-term effectiveness of the chemical dosage levels and reduction methods determined in the tests to be optimal will be studied, and capital and operating costs will be developed for various biofouling control measures.

Other alternatives to chlorine treatment are also being investigated. Two of the more novel approaches involve the use of iron ferrate and sulfur dioxide as biocides. The University of Miami has conducted two bench-scale test series (RP1261-3). In the first, the ability of aqueous sulfur dioxide systems to disinfect bacterial suspensions was investigated under controlled laboratory conditions. In the second, a bench-scale model of a flow-through condenser system was fabricated to evaluate the performance of iron ferrate in destroying laboratory-induced biofilms.

These bench-scale studies showed that aqueous sulfur dioxide can inactivate certain members of the microflora. However, substantial dosages (i.e., greater than 275 mg per liter) are required for acceptable levels of biofilm control. In experiments using iron ferrate, slime film retardation was observed. A dosage of slightly less than 2 mg per liter and a treatment frequency of once every 12 h appear to be optimal. For Lake Michigan waters, a treatment duration of 5 min was found to be effective in controlling film growth.

Because the number of variables that can be manipulated with the systems used in these studies is limited, the results must be considered preliminary. *Project Manager: Winston Chow*

R&D Status Report
ELECTRICAL SYSTEMS DIVISION

John J. Dougherty, Director

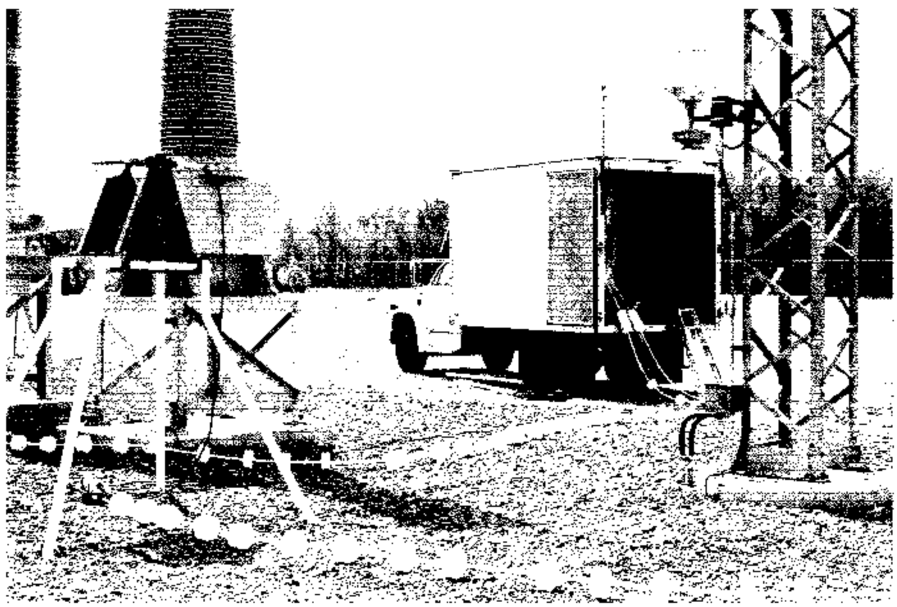
TRANSMISSION SUBSTATIONS

Substation control and protection

EPRI is sponsoring a project for the development of a digital control and protection system for transmission-class substations (RP1359). The project assumes the use of fiber optic communication links within substations so that electronic equipment (which handles the encoding and decoding of data and commands to be transmitted through the fibers) can be placed close to the high-voltage equipment in the switchyard. Although this concept is not new, any such system will have to survive the high electromagnetic interference (EMI) levels of the switchyard. A great deal of work has been devoted to this area in the last 20 years, but its focus was on conducted interference. There is still a lack of information about interference levels in general, particularly in the frequency range above a few megahertz.

At the outset of the project, a significant effort was concentrated on EMI work by Texas A. & M. University (RP1359-2). A special, truck-mounted measuring system was built. This system relies on instruments previously developed for military electromagnetic pulse (EMP) measurements. It is capable of recording electric and magnetic field components from two sensors with two different time bases for each sensor so that both short and long impulses can be studied. The triggering of the data-capture window can be varied within a wide range, ensuring that the worst transient is captured. The instrument system can record transients with a frequency content in excess of 100 MHz. Figure 1 shows the measuring setup.

Figure 1 Test setup of a mobile recording system to measure electromagnetic interference in high-voltage substations. The system is designed to measure transients or impulses of short duration (from a few nanoseconds to a few microseconds). A spherical, electric field sensor is in the left foreground. A short coaxial cable connects the sensor to a microwave transmitter placed on the ground below the sensor. The signals from the sensors are sent to the truck-mounted equipment through plastic (dielectric) microwave waveguides, seen rolled out on top of the ground. (The trailer can be rented by utilities at nominal cost.)



Tests have been conducted in 115-kV, 138-kV, 230-kV, 345-kV, and 500-kV switchyards. High-voltage laboratory tests were included in the test series to determine if the high-voltage laboratory can be used for prototype equipment tests. Also, in May 1980, Northern States Power Co. permitted participation in a staged fault test program, which provided valuable information that may make possible a comparison between the EMI caused by switching operations and fault-related EMI.

The analyses of the data confirm that high interference magnitudes exist in the 2–20 MHz range in high-voltage substations. The lowest frequencies exist in the switchyards with the highest voltage, but these also have the highest field strength. The analyses also indicate that the dominating interference originates from the bus system of the substation, which acts as an antenna that is excited by switching transients. The EMI is sufficiently high to interfere with the operation of unshielded electronic equipment. No significant EMI has been traced to arcing phenomena. Because the measurements have all been made within the substations in proximity to the high-voltage equipment, the electric and magnetic fields are not orthogonal, but this is to be expected in the near-field region of any antenna system.

As the ultimate objective of the EMI study was to develop a qualifying test that ensures survival of electronic equipment in a high-voltage switchyard, the existing test standards were reviewed to see if any could be used. Although there are many ways to test for electromagnetic compatibility (EMC), they all target specific compatibility problems, and none provides a good representation of the complex, time-domain waveforms seen in high-voltage switchyards. The type of test facilities used for EMP testing of military equipment would best represent the switchyard environment, but these test facilities are not readily available and would therefore not be realistic for testing utility products. The present thinking is that transverse electromagnetic (TEM) cells developed by the National Bureau of Standards may be the best tool for EMC testing of circuit board level assembly and that the high-voltage laboratory may be used for testing fully assembled systems. The TEM cell is useful primarily for frequency-domain types of tests, but the high-voltage laboratory would provide a time-domain type of test. Analysis and review are not yet fully completed, and the testing approach may change as more information is available.

It should be noted that conducted interference was excluded from this study because with the exception of current and potential transformer devices, all conducted interference is a result of the coupling between the bus system and the cables; that is, the electromagnetic field measurement obtained through this EMI study also describes the source for the conducted interference. The analysis of conducted interference must consider all pertinent cable parameters and is therefore very complex. Studies of conducted interference, however, have begun as a part of another EPRI project (RP1472) funded under the Distribution Program of the Electrical Systems Division. *Project Manager: Stig Nilsson*

Advanced operating mechanisms

Switching devices for substations historically have been operated by three types of mechanisms. These mechanisms use charged springs and pneumatic or hydraulic systems as an energy source. The power circuit breaker has been (and will continue to be) the major application for these mechanisms. However, each mechanism was designed to meet the requirements of the circuit breaker technology existing at the time of its development.

Today substation switching devices are changing, and these changes have created the need for new developments in operating mechanism technology. The use of the SF_6 gas, puffer-type circuit breaker, for example, is becoming dominant. This breaker requires much higher operating energies, faster contactspeeds, and freedom from the mechanical trip-free function. Transformer protective switches (a relatively new development) and fault current limiters (now under development) have still other requirements that create the need for new operating mechanisms. The demands of the puffer-type circuit breaker could be met by extending the range of existing power circuit breaker operating mechanisms. But this would result in considerably higher costs, greater auxiliary and operating power requirements, increased maintenance, and reduced reliability.

The source of energy for mechanism operation should be inexpensive, reliable, easily controlled, and should require small auxiliary and control power. Chemical propellants may meet these requirements if they are used as gas generators to supply the energy for new operating mechanisms. Although there has been limited application of this energy source to switching device mechanisms, it has been used for a broad range of industrial devices.

In May 1980 EPRI entered into a contract with Westinghouse Electric Corp. to develop operating mechanisms for substation switching devices using chemical propellants as the energy source (RP1719). The design of such a mechanism to operate an SF_6 gas puffer breaker will be reviewed by EPRI in the fall of 1981. This will include an evaluation of its cost-effectiveness, reliability, and applicability on electrical systems. If the design is acceptable, a prototype will be built. *Project Manager: Narain Hingorani*

Removal of PCBs from transformer oils

There are approximately 35 million distribution and power transformers in this country. It is estimated that between 5 and 20% of these (containing from 300 to 800 million gallons of oil) are contaminated with polychlorinated biphenyls (PCBs). PCB contamination is presently defined by the EPA as 50–500 parts per million (ppm).

If the general tenor of EPA regulations remains unchanged, it would be beneficial for the utilities to upgrade the oil in their transformers to bring them below the 50-ppm contamination level. This would permit repair work to be done in a normal manner and avoid costly cleanup procedures in case of an inadvertent spill.

Several chemical destruction or physical separation processes for PCB removal from transformer oil have been publicized to varying degrees. This is encouraging, but none show an awareness of the need to demonstrate that the treated oil will maintain the electrical integrity of valuable power transformers. During earlier EPRI transformer oil projects (RP562 and RP577) it was made clear that deficiencies existed in ASTM standards, so it would not be sufficient to use only ASTM standards for oil acceptability. Consequently, any process that proposes to treat the oil to eliminate PCBs and then reuse it in transformers would have to be carefully scrutinized.

EPRI has recently signed contracts for the removal of PCBs from transformer oils with General Electric Co. (RP2028-1) and Franklin Research Center (RP2028-2). In the General Electric project, four methods (two chemical destruction processes and two liquid extraction processes) will be evaluated on a laboratory scale. One will be chosen for scale-up based on technical merit, economics, and ease of interfacing both with the utilities' operations and with the outside world (local, state, and federal regulations). An additional service that will be provided under the General Electric contract is to test some transformer oils treated by other processes and ascertain whether these oils are suitable for reuse.

In the Franklin Research project, a unique liquid extraction process will be tested for treatment of contaminated oil. A minor study also will be made of adsorption of PCBs by solid adsorbents.

In a short-term study contract, also just getting under way, RTE Corp. will study equilibrium adsorption and rate of adsorption-desorption of PCBs on transformer insulation materials, particularly the cellulosic insulation. Knowledge gained here may enable us to accelerate the rate of desorption of PCB from the cellulosic insulation, thus permitting more rapid treatment of the oil.

This multipronged attack is slated to be completed in 12 months and should go far to alleviate the pressure on utilities to solve the PCB cleanup problem. *Project Manager: G. I. Addis*

Metal oxide surge arresters

Arresters play a vital role in protecting substation equipment from high-voltage surges. These surges can originate from either substation switching equipment or a lightning strike; in both cases, the resultant overvoltage needs to be limited through selective application of surge arresters on the electric power system. If the technology for the design and manufacture of surge arresters could be advanced to improve the protective characteristics and at the same time improve their reliability, significant savings could be realized. EPRI therefore initiated two research projects in 1975 to develop new arresters based on the metal oxide (ZnO varistor) technology. Varistors (variable resistors) have an extreme nonlinear resistive characteristic, which lends itself to gapless surge arrester designs.

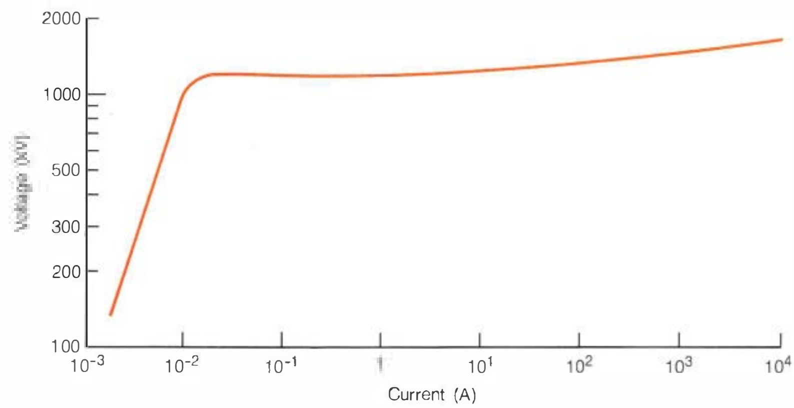
The first project, with McGraw Edison Co. (RP425-1), was sponsored to conduct basic research to study the effects of various chemical compositions and manufacturing processing variables used to make metal oxide varistor blocks. The contractor sought improvements in the electric properties, such as increased nonlinearity of the resistance, improved durability under high current, reduced leakage current under normal voltage, and improved stability to ensure long-term reliability. It was also felt that metal oxide varistor blocks could be made in sizes suitable for surge arresters, fault current limiters, and dc breakers, as well as for many future electric power system components requiring overvoltage protection and/or high transient energy absorption capability.

The second project, with Westinghouse (RP657-1), was sponsored to complement the McGraw Edison research project. In addition to the basic research, it sought to develop compositions and processes leading to the optimal and economical fabrication of large zinc oxide blocks and apply this advanced knowledge to meet all the requirements of a 1200-kV transmission system, providing a protection level of 1.5 times the normal voltage under switching surge conditions. Westinghouse was to demonstrate this knowledge by manufacturing, testing, and delivering to EPRI for field testing two 1200-kV and three 550-kV completely gapless metal oxide voltage limiters.

Both projects have been successfully completed, resulting in a good understanding of the manufacturing process. Zinc oxide is doped with small quantities of oxides of other metals, such as bismuth, antimony, chromium, nickel, manganese, or cobalt. These oxides are mixed, ground, and blended and then pressed into disk-shaped blocks that are fired in a high temperature kiln at about 1200°C. Next, an insulating collar is applied to the cylindrical surface to prevent external flashovers, and the flat faces are coated with a metallic conducting material; the blocks are stacked in a column of suitable height for the voltage application and then enclosed in a housing, such as porcelain, to form a surge arrester.

The voltage-current relationship characteristic of varistors is shown in Figure 2. The extreme nonlinearity permits direct use of a column of such varistor blocks for a gapless design. At the normal system voltage, a few milliamperes may flow through the varistors; however, as the voltage increases to or past the knee of this curve, the varistors go into a conductive mode, discharging thousands of amperes without letting the system voltage rise much beyond twice the normal voltage.

Figure 2 Volt-ampere characteristic for 1200-kV gapless metal oxide surge arrester shows minor current leakage up to critical voltage; after this point, the current increases without allowing a correspondingly large increase in system voltage.



Application of gapless arresters allows reduction in the insulation requirements (BIL) while opening up new opportunities from traditional insulation design concepts. For example, the designer can manipulate the varistor composition and processing to achieve the desired voltage limiting–energy absorption properties for any specific application. The process to manufacture varistor blocks is now fairly well understood, and detailed manufacturing procedures have been documented in EPRI report EL-1647 published in December 1980.

Westinghouse has manufactured 11-cm-diam blocks used in the prototype 1200-kV arresters. The first unit went into service at Bonneville Power Administration's Lyons transmission test facility in Oregon in September 1980. After extensive tests under lightning conditions at the BPA high-voltage laboratory, a second 1200-kV unit was installed at Lyons in May 1981. Three 550-kV ZnO arresters are being evaluated at the Tennessee Valley Authority's West Point, Mississippi, substation (Figure 3). On the strength of its success with this development, Westinghouse also designed a high-energy (30–40 MJ) series capacitor protection scheme for BPA.

The benefits to be derived by the industry through this development are the advantages of a truly solid-state arrester (i.e. reduced size and weight, simplicity, quick response, and ruggedness). Field testing will be easy because arrester leakage current can be used as a check of integrity (no gaps to spark over). Finally, station designers can more precisely predict arrester performance, and apparatus designers can more precisely calculate and possibly reduce the insulation requirements of substation equipment. These arresters are expected to be cost-competitive with gapped arresters initially and cheaper in the long run. *Project Manager: Vasu Tahiliani*

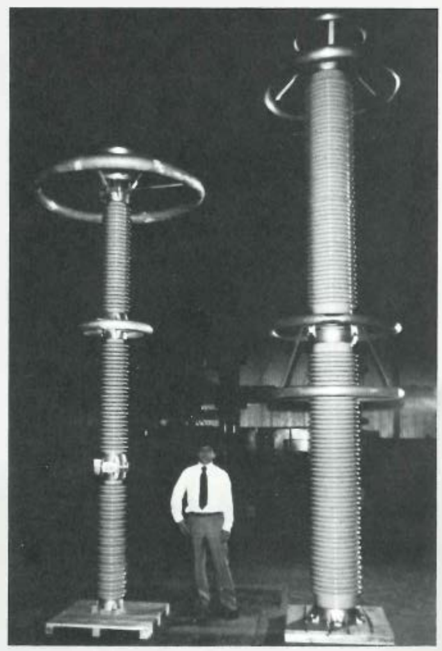


Figure 3 A conventional 396-kV surge arrester (left) alongside a 550-kV metal oxide system arrester.

Gas-insulated substations

SF_6-insulated substations have traditionally relied on conventional (gapped, silicon carbide) surge arresters for station protection, using porcelain-enclosed units external to the station wherever possible. When protection was needed within the station, as at a transformer at the end of a long SF_6 bus run, the conventional, sealed porcelain arrester was packaged within an SF_6 pressurized metal enclosure. This two-gas system leads to a very large, expensive package with inherently reduced reliability.

As mentioned in the preceding article, metal oxide has been successfully employed for the nonlinear elements in surge arresters. This sharper transition from insulating to conducting facilitates a gapless arrester design. This is a very important feature for gas-insulated stations because it can mean a single-gas (SF_6) design with smaller size, resulting in a reduced cost arrester design with increased reliability.

In 1978 a research project (RP1421-1) was initiated with Brown Boveri Electric to develop a metal oxide arrester for SF_6 gas-insulated stations (GIS). A companion project was also started with McGraw Edison to formulate and make the blocks required for the arrester design.

The objectives of the project were to develop the technology for thermally stable gapless arresters for GIS application over a wide (72–550 kV) range of voltages and to demonstrate the design principles through design and tests on a 362-kV prototype arrester.

A gapless metal oxide arrester for GIS applications has been successfully designed and tested. The following characteristics of this arrester have been identified.

- ▫ The active stack design employs the MOV blocks, soldered into modules, which are then stacked.
- ▫ A theoretical model has been developed and verified by measurement that accurately predicts the operating temperature of the metal enclosures filled with SF_6 gas.
- ▫ The temperatures along the metal oxide stack at operating voltage are predicted by a theoretical model and verified by measurement to be under 46°C at 28°C ambient. The theoretical model predicts stack temperature below 55°C at 40°C ambient.
- ▫ Ceramic capacitors achieve linear voltage grading along the arrester stack.
- ▫ Electric field analysis has been used to ensure that electric stresses will be below 4 kV/mm on all parts of the arrester at normal operating voltage.

This development work has significantly reduced the cost of the GIS arresters. They probably will cost a little more than conventional surge arresters that are applicable only on line entrance locations. Although the insulation coordination approach through arresters installed at line entrance may appear inexpensive, the trade-offs need to be carefully examined.

The lightning surges originating on the overhead line are of primary concern for the insulation specifications and dimensioning of the gas-insulated equipment. As only a fraction (typically one-third) of the incident traveling wave is transmitted into the GIS, the excessive overvoltages always result from successive reflections within the gas bus. And even though the arrester clamps the voltage to within a specified limit, it is possible to realize higher voltage levels within the gas bus. Further, as the service voltage and substation size increase, the lengths of the getaway buses to the overhead lines increase. This tends to reduce the protection provided by line termination arresters.

One should assess the advantages of applying arresters within a gas-insulated system to achieve the optimal placement of the arrester. If this approach permits a reduction in the insulation requirements or improves the system reliability through reliable overvoltage protection for the same insulation level, the overall economic trade-offs should be carefully examined before opting for the lowest initial cost of an air-insulated arrester positioned only at the line entrance.

In addition to the obvious cost reduction and improvements in reliability, by far the most significant benefit of the gapless arrester is its "soft" protective characteristics. Unlike the arrester designs employing series gaps, this design starts draining off the excess charge at a very low overvoltage level, inhibiting buildup of overvoltages that normally occur through successive reflections of a traveling wave within the gas bus. Also, since there are no abrupt voltage changes, the transients caused by arrester operation are minimized. *Project Manager: Vasu Tahiliani*

OVERHEAD TRANSMISSION

Drilled pier foundations

A drilled pier foundation typically consists of a cylindrical reinforced concrete pier, which is constructed by augering a hole in soil or rock, inserting a reinforcing cage, and backfilling the hole with concrete. The drilled pier foundation is widely used to support transmission line structures because it is simple to construct. When this foundation type is used in conjunction with a single shaft or H-frame structure, it is subjected to a high overturning moment, along with modest vertical and shear loads. Classical methods for predicting the load-deflection relationship for drilled piers consistently overpredict pier deflection. As the lengths and diameters of drilled piers are often governed by a maximum permissible deflection, many piers being installed today are very conservatively designed. Recognizing this situation, EPRI funded research to develop an improved method for designing drilled pier foundations subjected to high overturning moments (RP1280-1). GAI Consultants, Inc., was selected as the prime researcher on the project.

As noted above, the fundamental objective of this project was to develop an improved design/analysis methodology for laterally loaded drilled piers. To achieve this objective, the project was divided into the following four phases.

- ▫ Phase 1. Critique current methodologies for the design/analysis of laterally loaded drilled piers and develop an improved methodology.
- ▫ Phase 2. Develop a design/analysis computer program employing the improved methodology.
- ▫ Phase 3. Conduct instrumented load tests on prototype drilled piers.
- ▫ Phase 4. Develop theoretical predictions of the behavior of the test piers and compare with test results. Modify the design/analysis model and computer program, as appropriate, to obtain the best fit to the field data.

A state-of-the-art review of existing techniques for predicting the ultimate capacity and load-deflection response of laterally loaded piers, combined with a comparison of predictions based on these methods with existing test data, yielded some interesting results. For example, although the models currently used to predict ultimate capacity give similar predictions, there are few high-quality field tests to corroborate these ultimate capacity models. Further, the linear models used to predict the load-deflection response of laterally loaded drilled piers gave predictions that varied by a factor of 5. It appeared that the models predicting the smallest deflection were more accurate than the models giving larger deflections. Certainly, the suitability of a linear model for predicting deflections must be considered questionable in light of the observed nonlinear nature of the load-deflection response of test foundations. It was further determined that existing nonlinear models, if properly modified, may be able to capture the load-deflection response of laterally loaded drilled piers.

To expand the data base of high-quality test results, a field-testing program was conducted as part of this research project. Fourteen prototype drilled piers were subjected to high groundline moments, and 12 of these piers were tested to failure. The first test was sponsored by EPRI and was conducted as a shakedown test. Twelve of the 14 tests were cosponsored by various utilities in the United States, and one was sponsored by three midwestern utilities.

Results from the 14 tests yielded the following general conclusions.

- The test piers behaved essentially as rigid bodies.

- The relationship between the applied load and the deflection or rotation at the top of the pier is highly nonlinear.

- Most of the test piers did not exhibit a well-defined, fully plastic ultimate capacity.

- Two degrees of rotation at the top of the pier appears to be a reasonable uniform measure of ultimate lateral capacity.

- At a groundline moment equal to 50% of the ultimate moment, the nonrecoverable deflection is approximately 50% of the total deflection.

Soil-structure interaction for a laterally loaded drilled pier involves a complex distribution of stresses at the pier-soil interface. The solution to this problem is further complicated by the nonlinearity induced by slip and separation at the pier-soil interface. Although continuum model solutions (such as the finite element method) are feasible, continuum techniques are not practical for day-to-day design.

A design/analysis computer program was developed for laterally loaded piers: PADLL (pier analysis and design for lateral loads) can treat both flexible and rigid piers embedded in multilayered subsurface profiles. It incorporates a four-spring model in combination with a finite element beam model for the pier. Analysis options include ultimate capacity analysis and nonlinear load deflection analysis. In addition, the code can design a pier (select depth and diameter) and satisfy selected performance criteria, such as minimum diameter or minimum concrete volume.

PADLL was used to design a pier embedded in medium-dense–to–dense sand where the water table is well below the base of the pier. The pier loads consist of a 1000 kp-ft (1356 kNm) groundline moment and a lateral shear of 10 kp (44.5 kN). Pier groundline deflection under these loads had to be less than 1 in (25 mm). The resultant design consisted of a 5-ft-diam (1.5-m) pier embedded 11 ft (3.35 m) in the ground. A nonlinear load deflection plot for this pier, as produced by PADLL, is presented in Figure 4.

The result of this work should be lower-cost, yet reliable, transmission tower foundations. In fact, Jersey Central Power & Light Co. expects to save nearly $1 million on an 83-mile line to be constructed between 1983 and 1987. Regional transmission tower foundation design seminars will be sponsored by EPRI early in 1982, at which utility personnel will be able to use the computer programs during design exercises. The foundation design seminars will also present information on uplift and compression foundation produced by another EPRI-sponsored project. Emphasis is being placed on training utility instructors in the use of these improved foundation design procedures. A self-contained videotape training program will be distributed, which participants can take back to their companies for further dissemination. *Project Manager: Phillip Landers*

POWER SYSTEM PLANNING AND OPERATIONS

Bulk power transmission outage data

The reliability of a bulk power transmission system can best be assessed by collecting and organizing accurate outage data for the components that compose the system. Uniform definitions and reporting procedures are needed so the output of various data collection efforts can be compared. This should be assembled in a well-structured data base.

A two-year project recently completed by General Electric (RP1283) developed defini-

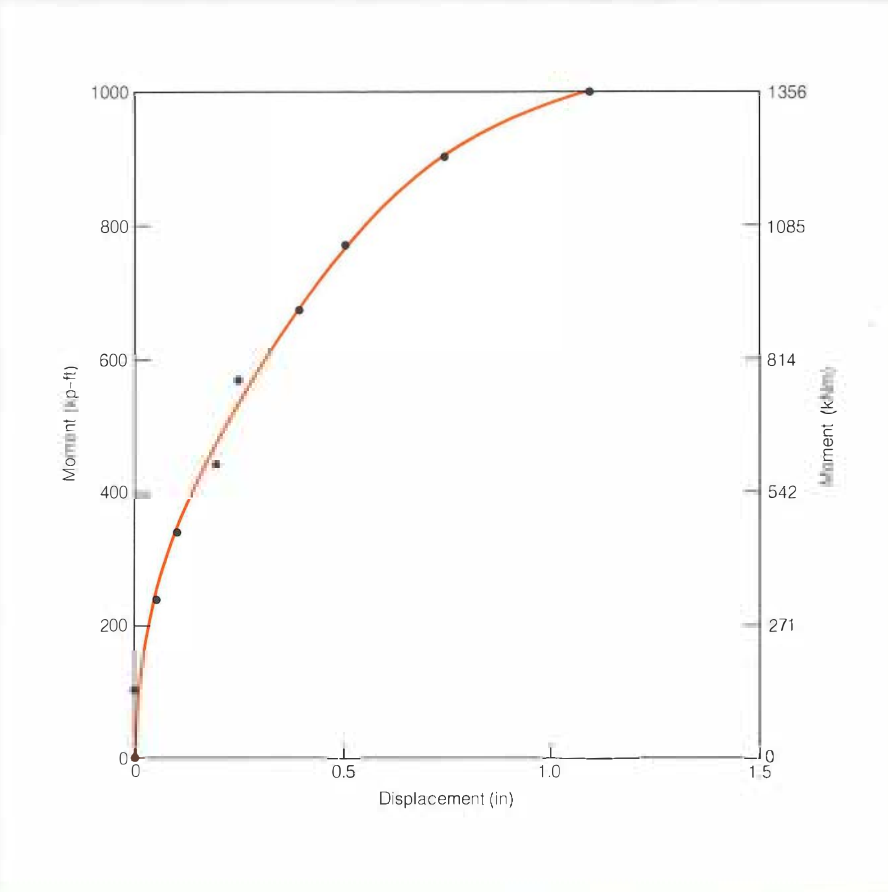


Figure 4 Nonlinear load-deflection plot for a 5-ft-diam (1.5-m) pier embedded 11 ft (3.35 m) deep that was produced by PADLL, a computer program for foundation design.

tions, formats, and procedures for just such a use in the collection of outage data on transmission systems. The project consisted of four interrelated phases. Phase 1 reviewed current industry practices for collecting, storing, processing, updating, and using bulk transmission system outage data. Phase 2 determined the raw data requirements for reliability calculations of bulk transmission systems. Phase 3 produced the design of a flexible outage reporting approach and the formats for collecting outage data. Phase 4 evaluated different generic data base structures and proposed a data management system.

The results of this project also formed a basis for data collection by individual utilities and for pooling data into a larger data bank; this basis is available in a final report, EPRI EL-1797. It was not the intent of this project to actually collect data, to implement reporting procedures, or to develop planning or operating standards for an outage data base.

The proposed method for recording outage events is a multilevel approach that allows utilities to begin recording data at the highest bulk power system voltage level and then extend to lower voltage levels, consistent with need, cost, and data availability. The collection of data at increasing levels of complexity will thus permit users to phase-in their data collection effort. Typical sources of basic information on transmission system outages are the system dispatcher's log and protection system reports, supplemented by the supervisory control and data acquisition (SCADA) system.

The data collection effort spans functional and organizational boundaries within a company, and the complete data on an outage event will be available only over a period of time as incidents are analyzed and reported by the several responsible groups within a company.

Recommendations for future research include initiation of a pilot transmission data collection effort with an electric utility and extended efforts on development of models for outages in order to define more precisely the necessary data. *Project Manager: Neal Balu*

Reliability indexes for power systems

The evolution of criteria for planning generation, transmission, and distribution systems has led to the development of reliability indexes that are responsive to the basic planning parameters. The primary purpose of reliability indexes is to serve as a basis for power system planning. If an index can be shown to aid in the planning decision-making process, and if computation of the index is economically practical, then system planners can be expected to use them. Today's increased cost of new facilities, scarcity of capital, and concerns with environmental issues have led to an intense interest in the development of reliability indexes that measure the impact on the ultimate customer. At least one potential advantage of reliability indexes would be to serve as a basis for an objective comparison of the reliability of alternative system configurations.

This project (RP1353) developed analytic expressions and computation requirements for bulk power system reliability indexes and applied the indexes to a simplified utility test system. During the development, primary consideration was given to whether the indexes accurately reflected the kind of service the customer was getting, their value in estimating the worth of reliable service, whether they were helpful in communicating with nontechnical people or were easy to compute. As a result, four primary indexes were selected: (1) expected hourly loss of load, (2) expected energy not supplied, (3) frequency of loss of load, and (4) expected number of customers cut off. All these are on an annual basis.

The final report for this project (EPRI EL-1773) can serve as a handbook for power system planners because the reliability indexes most basic to the electric utility industry have been identified and given firm mathematical definitions. *Project Manager: Neal Balu*

R&D Status Report
ENERGY ANALYSIS AND ENVIRONMENT DIVISION

René Malès, Director

PARTICLE CHARACTERIZATION

High-temperature fossil fuel combustion produces a wide variety of gaseous and particulate pollutants, some of which can affect health, ecology, and materials. To assess the significant effects of fossil-fuel-fired power plants on the environment, it is essential to recognize the physicochemical forms of the responsible pollutants and the amounts that produce such effects. As part of its air quality research, EPRI's Environmental Physics and Chemistry Program is studying the physicochemistry of particles emitted from fossil-fuel-fired power plants.

The purpose of this study of power plant emissions is to characterize airborne particulate pollutants to determine their potential effects on the environment. Areas of particular interest are the following.

- Human health: assessing potential respiratory system damage, eye irritation, and general toxicity
- Plant and animal toxicology: determining the availability of particulate pollutants' harmful constituents in wet or dry deposition
- Environmental risk and issues analysis: determining pollutant composition, as damage depends on chemical species and dosage
- Visibility: determining particle size, morphology, and surface composition to predict light scattering and visibility impairment
- Material defacement and damage: determining whether particulate deposition results in either defacement or real material damage
- Control technology: assessing electrical conductivity for electrostatic precipitators and catalyst poisoning for NO_x control; determining combustion parameters (e.g., temperature, coal type, oxidizing conditions)

Because no one technique or instrument can completely analyze a complex aerosol sample, a number of complementary instruments are being used to measure particle size, morphology, and bulk and nonbulk (micro) physical and chemical composition. A detailed discussion of the various analytic techniques is beyond the scope of this status report, but Table 1 lists the more commonly used tools for particle analysis.

The program supports a number of projects to characterize the bulk composition of atmospheric particles. Methodologies for the analysis of polycylic aromatic organic compounds on or in fly ash are being developed (RP1057). Results to date indicate that high molecular mass polycylic aromatic hydrocarbons are strongly bonded on fly ash; solvent extractable organic species appear to be highly polar and/or macromolecular. Two other projects have produced measurements of trace organic compounds in the Los Angeles and New York City air (RP1315 and RP1222). More than 100 organic species have been identified. Studies are under way to characterize particles generated by coal gasification (RP1617) and to determine the concentration and type of organic species emitted from cooling towers (RP1744).

Two projects and one technical planning study are concerned with improving the analysis of organic compounds on or in fly ash. In one project researchers have been able to use matrix isolation spectroscopy to distinguish polycylic aromatic hydrocarbon isomers without sample fractionation (RP1307). The other project is investigating the magnitude of any artifact problem associated with sampling airborne organics by using glass-fiber filters (RP1795). Tandem mass spectrometry appears most promising as a complement to gas chromatography–mass spectrometry and high-performance liquid chromatography for the analysis of organic compounds in fly ash (TPS81-778).

Nonbulk (micro) characterization of atmospheric particles is being done by sophisticated state-of-the-art techniques (RP1625). Individual particle morphology, size, and bulk element composition are relatively easy to measure with scanning electron microscopy and energy dispersive X-ray fluorescence. Surface analysis, depth profiling, and chemical composition are much more difficult. Preliminary measurements indicate that the composition of the top 20 nm of in-stack fly ash is quite different from the composition of the particle interior. A novel technique whereby a fly ash particle beam (from an aerosol generator) is introduced into a modified mass spectrometer may allow the speciation of organic and inorganic compounds in or on individual particles (TSP81-783).

A study to design sampling and analysis procedures for in-stack coal combustion products includes both bulk and nonbulk particle characterization (RP1776). This project is designed to provide statistically valid procedures and guidance for health and ecological effects studies, as well as for control technology development. In-stack sampling and analysis are still required to determine the relationship between primary emissions and the secondary products formed from the primary pollutants.

Future research will be directed toward two goals: (1) determining the utility contribution of pollutants to the environment at various geographic points and (2) measuring pollutants' potential harmfulness. To accomplish the first goal, source-receptor modeling will be used to complement ongoing dispersion-plume modeling. Regardless of the mathematical approach used, receptor modeling requires knowledge of source characteristics ("fingerprints" or markers). Physicochemical measurements at a chosen site should then allow calculation of the utility contribution. One promising methodology requires the measurement of particle element concentration. If the concentrations are too similar, it would then be necessary to measure compound, ion, isotopic abundance ($^{14}C/^{12}C$), and particle size–morphology. Accomplishing the second goal, guiding health and ecological experiments, also relies on speciation data and requires the collection or simulation of substantial quantities of utility fly ash for toxicologic studies. Consequently, a major effort has begun to sample and characterize in-stack coal combustion products.

Research will continue to develop instrumentation and techniques for particle char-

Table 1
COMMON ANALYTIC TECHNIQUES

Particle-Size Measurement (in order of increasing size resolution)	Nonbulk Microanalysis (in order of increasing surface sensitivity)	Bulk Analysis (in order of increasing general sensitivity)
Sonic sieve	Scanning laser acoustic microscopy	Noninstrumental standard analysis
Cyclone	Light microscopy	Brunauer Emmett Teller (BET) surface area measurement
Coulter counter	Laser Raman microprobe	Thermal gravimetric analysis
Babco multiparticle classifier	Laser microprobe mass analysis	Differential thermal analysis
Light microscopy	Scanning electron microscopy wavelength dispersive X-ray* energy dispersive X-ray	Phosphorescence
Laser methods	Scanning transmission electron microscopy electron diffraction electron energy loss spectroscopy energy dispersive X-ray	Photoacoustic spectroscopy
Centrifuge	Ultraviolet photoelectron spectroscopy	Matrix isolation spectroscopy
Cascade impactor	X-ray photoelectron spectroscopy	X-ray diffraction
Electrical aerosol size analyzer	Low-energy electron diffraction	Electron paramagnetic resonance
Screen diffusion battery	Scanning Auger electron spectroscopy†	Nuclear magnetic resonance
Scanning electron microscopy	Sputter-induced photon spectroscopy	Raman spectroscopy
Scanning transmission electron microscopy	Ion microprobe mass analysis	Infrared spectroscopy Fourier-transform
	Secondary ion mass spectrometry	X-ray fluorescence particle-induced X-ray emission ultraviolet visible
	Scanning electron stimulated desorption	Thin-layer chromatography
	Ion scattering spectroscopy	Ion-exchange chromatography
		Liquid chromatography high-performance preparatory column
		Gas chromatography packed column capillary column
		Emission spectroscopy inductively coupled plasma arc-spark flame
		Atomic absorption spectroscopy
		Instrumental activation analysis neutron gamma ray high-energy-charged particles
		Mass spectrometry

*The ultimate form of the electron microprobe.
†The ultimate form of Auger electron spectroscopy.

acterization. Although the last five years have shown excellent progress in improving detection sensitivity, speciation remains difficult. Improvements in capillary gas chromatography and specialized mass spectrometry and high-performance liquid chromatography will be the workhorses for the next few years. However, other techniques, such as Fourier-transform infrared, nuclear magnetic resonance, matrix isolation spectroscopy, and Raman spectrometries, will also be examined. *Project Manager: Jacques Guertin*

FUEL TRANSPORTATION

Rapid changes in prices, fuel availability, and fuel-use regulations have drastically altered plans for providing the nation's future electricity generation mix. As a result, industry experts are considering new fuel sources, which may create new demands for fuel transportation. Projected increases in the utilities' consumption of coal, for example, may jeopardize the ability of the nation's rail and water transportation network to reliably service these demands.

To meet this potential problem the Supply Program has begun to investigate future availability, potential costs, and needed investments in the transportation network. Preliminary studies indicated that if there are large increases in transport load and if no actions are taken to upgrade current transport facilities, rail and water transportation systems could be congested in certain locations and thus limit increases in coal use by utilities.

The preliminary studies were based on engineering cost models, which were constructed to examine point-to-point unit costs for rail and water coal shipment and to examine alternative routes for circumventing bottlenecks. These studies indicated that a more thorough analysis of capacity, as well as a better understanding of future coal transport costs and their relationship to the volume of other commodities transported, was needed.

In a recent study, two network representations of the transportation system were developed to examine the interactions between coal and other commodities (RP1219). The networks consist of a set of nodes representing suppliers, users, interfaces between railroads and waterways, and other critical points in the transportation system. The nodes are connected by a series of links representing segments of the railroad and waterway systems. These networks were developed for region-to-region or corridor analysis and for specific rail routing from mine-to-plant analysis.

The corridor network has 863 railroad nodes and 1401 links. The more detailed network has 1591 nodes and 3198 links representing the rail network. In both networks the waterways are represented by 416 nodes and 421 links. For each of these nodes and links, a series of functions have been developed that describe cost, time, and energy use as a function of the quantity shipped. These functions reflect the impact of congestion.

Figure 1 is an example of 1990 cost functions used in the model to represent the eastern region railroad links with centralized track control. Four functions are described, depicting combinations of terrain and trackage. Costs for through and unit trains are given as functions of total traffic volume over these classes of links. The upward sloping portion of each curve reflects the increasing costs caused by congestion. The representative values for practical capacities are also noted. (It is possible for a link to carry more volume than the practical capacity, but this results in such problems as delayed orders and hence higher costs.)

Figure 1 Cost functions in 1990 for the eastern region railroad links with centralized track control.

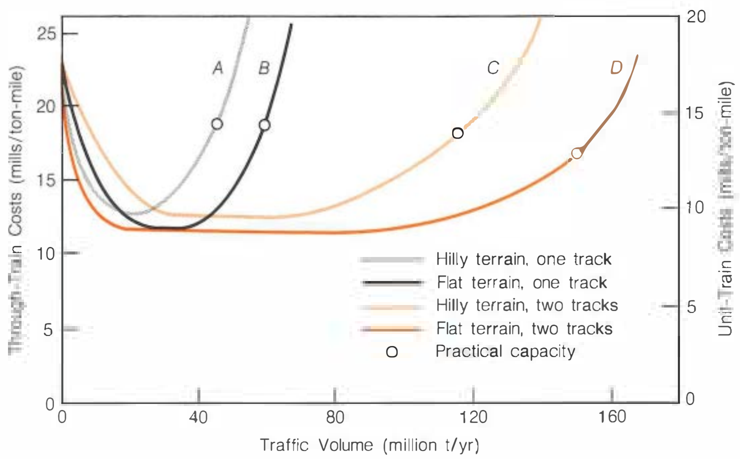


Table 2
INTERREGIONAL COAL SHIPMENTS

	1980	1990	2000
Volume (billion tons)	0.62	1.1	2.1
Average cost ($/t in 1980 $)	11.90	13.10	13.60
Average distance (mi)	792	909	844

The effects of terrain can be seen by examining the differences between either curves A and B, or curves C and D. Likewise, the effects of doubling the number of tracks can be seen to greatly increase the amount of traffic that can flow over links in a network. The functions also vary with time to reflect ongoing and proposed transportation system changes. For example, a rail cost function may be shifted between 1980 and 1990 to reflect improved switching and signaling systems or a track upgrade.

Data on commodity movements have also been developed, based on 172 Bureau of Economic Analysis regions. Some of these BEA regions are subdivided to represent important supply points for coal, such as Gillette, Wyoming. To examine the relationship of coal to other types of commodities shipped over the network, shipment data have been gathered and consolidated into 18 types of other commodities for 1980, 1985, 1990, and 2000. Information describing both coal unit-train and through-train movements has also been developed over the network for these years. These data are inputs for two models: the transportation network model (TNM) and the railroad routing model (RRRM).

The purpose of TNM is to reflect as faithfully as possible the operation of the nation's multimodal transportation system. It routes given intercity commodity movements through a transportation network whose components have properties that are well defined. This is the function of the shipment and network data described above. TNM can be used with either of the two network data sets. The impact of aggregation can be assessed because every node on the corridor-level data set is also a node on the more detailed data set.

The purpose of RRRM is to provide detailed information of specific source-to-sink coal train movements. RRRM has a more complex searching algorithm that uses ownership of railroad lines. (In current industry practice, ownership is an important factor for determining a specific route.) RRRM is used only with the more detailed data set.

The two models have been used to analyze current and future transportation patterns and problems. TNM was calibrated with 1978 published data on transportation movements. Model outputs for 1980 were compared with these data to ensure the model was replicating the transportation system behavior. This calibration included the development of the special regions for coal supply hauling, identification of changes that would affect the node and link functions because of current and proposed legislation, and an overall check of all input data. After model calibration was completed, several analyses were performed.

TNM was run for the years 1980, 1990, and 2000 and the resultant transportation needs were evaluated to provide the baseline scenario summarized in Table 2. Standard model outputs provide a wealth of information on costs, times, energy use, and specific shipment paths. These were compared with present and projected capacity to determine system bottlenecks.

Subsequent analyses examined in depth railroad routings for the year 1990. RRRM was run and compared with the results from the 1990 TNM. After the calibration was complete, the effects of proposed railroad mergers were analyzed to determine the impact on factors affecting coal transportation.

Special nodes and links were constructed to represent coal slurry pipelines and a model run was made for 1990 to determine the potential effects of two proposed pipelines: ETSI from Gillette, Wyoming, to White Bluff, Arkansas, and the Texas Eastern Line from southern Montana to the Gulf Coast. As a result of assigning coal to these pipelines, the transportation costs of noncoal commodities as reflected by the models were reduced slightly and the average time for moving them was improved by 13%. Total costs for moving unit-train coal decreased slightly and for individual shippers using the slurry pipelines, cost savings ranged from $1.06 to $3.67 per ton in this corridor.

The models and data are currently being prepared for use by EPRI and others. Initially, they will reside on a Control Data Corp. machine and are written in Simscript II.5. The previous project on cost models for coal transportation (RP866) developed engineering cost models for rail and water hauling of coal, which are written in FORTRAN IV and are available from EPRI in card form. Although the emphasis of the research has been on coal, other fuels have also been considered. The gas pipeline transmission system was modeled and examined (RP944). The network approach was also employed to enable users to evaluate the transportation options for new projects, such as gasification plants or LNG terminals.

Potential problems concerning tanker fleet supply for carrying LNG and crude oil were evaluated for the 1980s. These projects are part of an ongoing program in transportation research at EPRI. Future projects will be aimed at improving knowledge of the present and future structure of the transportation industry and the manner in which costs will change. *Project Manager: Edward Altouney*

R&D Status Report
ENERGY MANAGEMENT AND UTILIZATION DIVISION

Fritz Kalhammer, Director

SYSTEM ANALYSIS FOR ENERGY STORAGE

If the target cost and performance goals of advanced energy storage technologies are met, these technologies will represent an important generation alternative for electric utilities, providing low-cost peaking capacity through the efficient use of coal-fired and nuclear baseload units. Storage technologies can also be designed to offer power system dispatchers considerable operational flexibility. For instance, the conventional pumped-hydro power plant, because of its fast rate of response to load demand and its ability to withstand cyclic load duties, is in many cases being used to perform load following and to provide the capacity for frequency regulation and spinning reserve. Although advanced storage technologies, such as battery energy storage and compressed-air energy storage (CAES), are similar to conventional pumped hydro in many respects, they will interact with power systems differently. Thus, to provide utilities with a realistic assessment of the functions advanced storage technologies can perform and, to the extent possible, to quantify the associated cost benefits, EPRI's Energy Management and Utilization Division is sponsoring a series of system planning and operations studies. The overall objective is to maximize the benefits of advanced storage for utilities.

Research supported by the Energy Management and Utilization Division includes efforts toward the development of several advanced battery storage concepts and the commercialization of CAES and underground pumped-hydro storage. A major thrust in advanced battery storage development is the scale-up of laboratory-size battery cells to commercial size and the thorough shakedown testing of a large quantity of these commercial cells at the Battery Energy Storage Test Facility. If the tests indicate that advanced batteries meet performance and reliability goals and that mass-production techniques can reduce their cost sufficiently, the batteries may be commercially available by the late 1980s. In parallel with these technology development efforts, several system studies are being conducted to explore the roles advanced batteries may play in a power system. Specifically, the potential of batteries to provide capacity for frequency regulation and spinning reserve, to reinforce transmission systems, and to suppress power system subsynchronous resonance has been investigated.

CAES is a commercially mature technology in the sense that no major technological problems exist to prevent the construction of a full-size (200-MW) plant in the United States. EPRI's role has been to support research activities to further improve CAES performance and reliability and to coordinate engineering design and system analysis activities for several electric utilities who have expressed interest in building the country's first CAES plant. System analysis efforts include the development of computer software to determine the most economic CAES dispatch strategy.

System analysis for advanced battery storage

Advanced battery storage power plants will have three distinguishing characteristics. First, the plants, in particular those with sodium-sulfur batteries, will have an extremely fast rate of response (typically several orders of magnitude faster than conventional generation technologies). This unique capability opens up a wide spectrum of potential applications, from stabilizing the electrical network to providing the capacity for power system frequency regulation and spinning reserve. Second, because of their excellent environmental characteristics, battery energy storage plants could be installed near load centers. This would enable them to be used at strategic locations in a network to provide reinforcement for the transmission system and to minimize transmission losses. Third, battery storage power plants will have an economic storage capacity of around 5 hours. Thus system dispatchers will need a strategy for operating the plants during summer peaks, which typically last 10 hours or more.

System studies have addressed these characteristics and the potential benefits and requirements they entail.

Operating Strategy A major goal of the system analysis effort is to develop an operating strategy for battery storage to meet the following utility objectives.

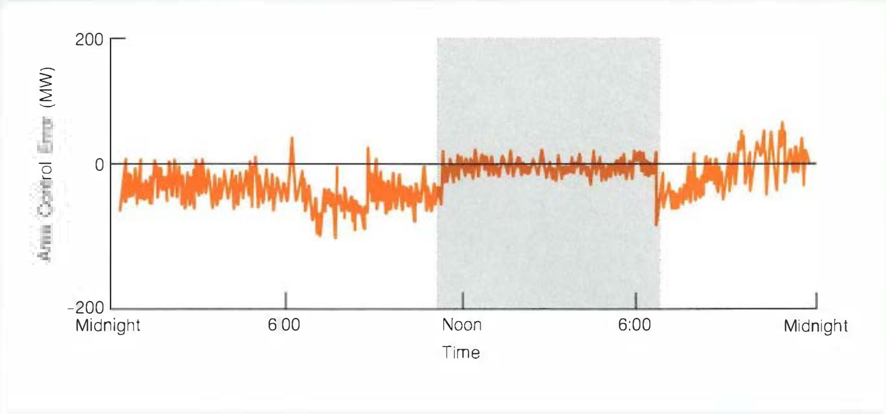
- Peak shaving—including summer peaks, which may last 10 hours or more
- Fuel displacement—use of batteries for storing off-peak, low-cost baseload coal or nuclear electric energy to displace on-peak oil-fired generation
- System spinning reserve—use of the converter capacity to provide for system spinning reserve and thus improve overall system generation efficiency
- Frequency regulation—cycling of battery storage plants for tie-line bias control to reduce the cyclic duties imposed on other generation units

In TPS77-782, a hybrid computer at the University of Missouri was used to model the dispatch control operations of a major power pool. The computer was developed by EPRI's Electrical Systems Division and is currently being used in training power dispatchers. The operating characteristics of a 250-MW sodium-sulfur battery and its power-conditioning system were modeled. The dispatch logic was such that during peak periods, the battery power plant maintained an average output level of about 50% of its maximum capacity. The unused capacity was held in reserve to meet the system spinning requirements and to provide for frequency regulation. Thus the battery power plant was subjected to very severe cyclic duty. The objective of the simulation study was to determine whether a battery power plant could tolerate this cyclic duty without damage to the battery cells and whether power system frequency regulation would suffer in this mode of operation (i.e., whether the area control error would deteriorate).

The computer simulated battery operation and its impact on power pool operation. Data on the cyclic load duty were recorded on magnetic tape and sent to a battery manufacturer for review. The manufacturer concluded that the thermal stresses imposed by this duty were well within the design limits of the battery cells. Thus it appears that sodium-sulfur battery systems can be subjected to cyclic loading without loss of battery life or efficiency.

The results on frequency regulation are illustrated in Figure 1. It shows that during the period between 11:00 a.m. and 7:00 p.m., when the batteries were being used for tie-line bias control, the power pool's area control error was much improved. These results were presented to the North American Power System Interconnection Committee, the largest professional organization of power system operators in the United States.

Figure 1 Results from a computer simulation of the use of advanced sodium-sulfur batteries for tie-line bias control. The area control error was improved when the batteries performed this task (shaded area).



On the basis of this study, it can be concluded that sodium-sulfur battery storage power plants can meet the severe cyclic duties imposed by frequency regulation and that this mode of operation results in improved power system performance. In a related effort, a system planning study was undertaken to develop reliable estimates of the cost savings that could accrue to utilities if advanced batteries were used to meet spinning reserve requirements, thereby allowing other units to be operated more efficiently (RP1084-3). Figure 2 presents a simplified explanation of why providing spinning reserve capacity is costly.

The study was conducted by Energy Management Associates, Inc., with cooperation from the planning departments of five electric utilities, which provided data for the analysis and reviewed and approved the results. These utilities represent a wide range of system generation mix. The savings projected to result from the use of advanced batteries to meet spinning reserve requirements, in dollars per kW of battery capacity, ranged from a high of \$25/kW per year (for a utility with a large percentage of generation capacity in combustion turbines) to no savings (for a utility with a large hydro generation base). The average estimated savings for four of the five utilities was about \$15/kW per year, which translates to a life-cycle credit of about \$75/kW for the advanced batteries, a very significant amount.

The results of TPS77-782 and RP1084-3 were used to develop a conceptual operating strategy for battery storage power plants to meet the four utility requirements: peak shaving, fuel displacement, provision of spinning reserve, and frequency regulation. This strategy, which is illustrated in Figure 3, calls for battery power plants to be charged off-peak by using baseload generation units that are idled or whose output is reduced for the nighttime low-load period. During the morning pickup period, the battery power plant reverses from charging to discharging, thereby providing the system with ramping capability. Because of the reversal from charging to discharging, this capability is equal to at least twice the battery's output capacity.

During the peak period, the battery storage plant discharges at about half its rated capacity. For instance, a 100-MW battery storage power plant with 500 MWh of storage capacity will be generating at an average rate of about 45 MW. The other 55 MW will be held back to provide the capacity for spinning reserve and frequency regulation. This enables the more efficient use of intermediate units, whose output would otherwise be reduced to meet spinning reserve requirements. Because the peak lasts over 10 hours, the battery storage power plant will still completely discharge its stored energy of 500 MWh even at the reduced rate of output; therefore the full potential for displacing on-peak oil-fired generation will be realized.

Transmission System Impacts Battery energy storage plants promise to have a com-

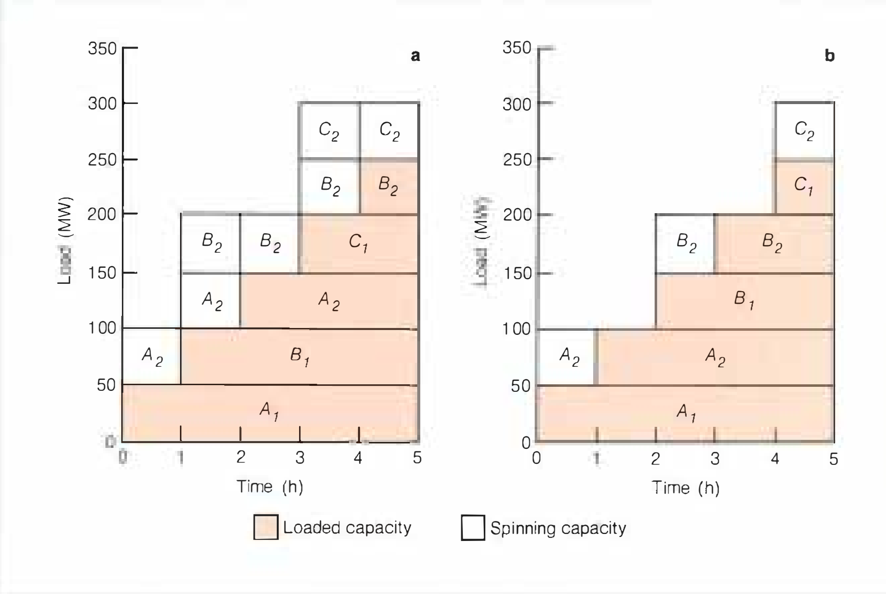
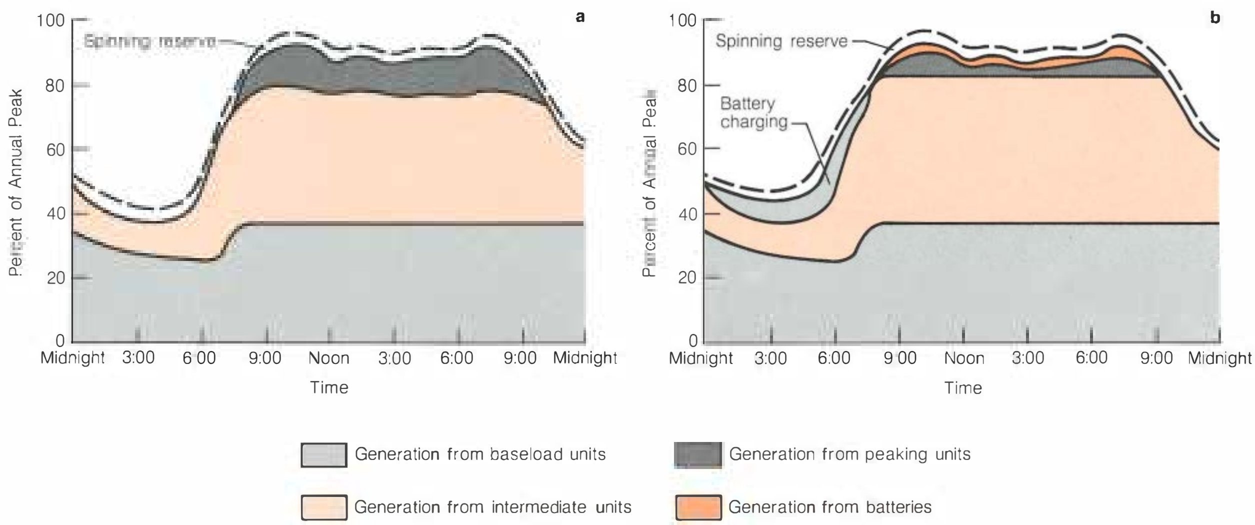


Figure 2 Effect of system spinning reserve requirements on dispatch sequence. *A* represents a baseload unit, *B* an intermediate unit, and *C* a peaking unit. A_1, B_1, and C_1 represent the minimum unit load levels, and A_2, B_2, and C_2 the other unit load levels. With a 20-MW system spinning reserve requirement **(a)**, the dispatch sequence is A_1, B_1, A_2, C_1, B_2. If there were no system requirement for spinning reserve **(b)**, the units could be dispatched in the most efficient and economic sequence: A_1, A_2, B_1, B_2, C_1. The use of advanced batteries to meet spinning reserve requirements could enable such optimal unit dispatch.

Figure 3 Operating strategy for advanced battery storage power plants. Without battery storage **(a)**, the output from intermediate units is reduced below capacity to provide for spinning reserve during the peak period (from around 9:00 a.m. to 9:00 p.m.); thus more generation from inefficient peaking units is required. Batteries could be used both to meet part of the peak demand and to provide for spinning reserve requirements during the peak period **(b)**. This would enable intermediate units to be used more efficiently and peaking generation to be reduced. The batteries would be charged off-peak by baseload units, which would be a more efficient use of that capacity.



bination of operating, economic, and environmental characteristics that will give them unique siting flexibility, including the possibility of urban and suburban siting. This flexibility will offer utility planners opportunities for deploying energy storage plants at strategic locations in a power system where transmission bottlenecks exist. Such a strategy could result in significant savings or deferred transmission investments.

Systems Control, Inc., has conducted a planning study to develop realistic estimates of the transmission savings that could result from installing dispersed battery storage power plants in a utility system. To the extent possible, traditional utility transmission planning approaches and economic analysis methodologies were adopted for this study.

The results indicate that dispersed battery power plants could achieve significant transmission savings, ranging from \$66 to \$133 per kW of the generating capacity of the battery installation. Because of the great diversity of utility systems, these results cannot be expected to be generally applicable. However, the results are believed to be a good indication of the average transmission savings that could accrue to a large number of utilities from the use of dispersed storage plants.

System analysis for CAES

CAES introduces an added level of complexity to the optimization of power plant dispatch, primarily because unlike any other form of energy storage, it consumes fuel during its generation cycle. For every kWh of energy consumed during the charging cycle (and stored in the form of compressed air), about 1.3 kWh will be produced during the generation cycle, with some portion of the energy coming from the supplementary fuel. Factors to be considered in making CAES operating decisions include the cost of the charging energy, the round trip efficiency, the cost of fuel consumed during generation, the cost of the peaking generation that will be displaced by CAES, and the outage probability for all generation units, which affects all the preceding costs.

EPRI's goal in supporting system analysis for CAES is to provide technical assistance to electric utilities who are interested in assessing the technology. This assistance has taken two forms: computer software to help determine the impact of CAES on a utility's power generation costs and preliminary system planning studies.

Under RP1084-3 Energy Management Associates has developed a computer module to assist utilities in assessing the production cost savings of operating a CAES system as part of their generation mix. The module has been tested for reliability and accuracy by Commonwealth Edison Co. and Potomac Electric Power Co. and to date has been successfully used by four utility groups in CAES economic assessments.

A preliminary system planning analysis of CAES is being conducted for 8 small utilities (municipals, rural electric cooperatives, and generation and transmission cooperatives) selected in an initial screening of over 40 small utilities (RP1084-6). The study makes an economic assessment of installing CAES versus installing combustion turbines and/or purchasing power. The preliminary results show a high break-even cost for CAES, which exceeds its estimated installed cost for those small utilities that have a high demand charge coupled with low off-peak energy charges. Next in this ongoing project, EPRI will solicit 3 or 4 of the 8 utilities to share the costs of an in-depth economic feasibility assessment.

By helping utility planners assess the economics of advanced storage technologies, system analysis is expediting their commercial introduction. It is also informing manufacturers about the functional characteristics that should be aimed for in designing commercial advanced storage technologies. *Project Manager: Timothy Yau*

R&D Status Report
NUCLEAR POWER DIVISION

John J. Taylor, Director

HIGH-TEMPERATURE FILTRATION

The application of high-temperature filtration (HTF) techniques to process streams in LWR power plants has the potential to significantly reduce radiation buildup and occupational exposure in these plants. Conventional filtration and purification methods use ion-exchange resins and are limited to temperatures below 50°C (120°F). To apply these methods to systems operating above this temperature, the process stream must be cooled. HTF offers a means of purifying at high flow rates without this thermal penalty. There are three basic approaches to HTF: electromagnetic filtration (EMF), edge-type mechanical filtration, and graphite deep-bed filtration. EPRI's work in this area focuses on EMF technology (RP1445).

Corrosion-product contamination

Corrosion-product contaminants within the nuclear cycle are the primary source of radioactivity associated with out-of-core surfaces. As the metals of the system corrode, impurities are released to the process stream and can deposit on fuel surfaces. While residing in the core, these impurities can be activated to radioactive isotopes. If this material becomes resuspended in the primary coolant, it can deposit on out-of-core plant surfaces. Such deposits are the primary source of plant radiation fields.

Most of the corrosion products present in the waters of power plant systems have magnetic susceptibility and exist as particulates. The magnetic susceptibility of these products varies with the species. In PWRs the principal primary-system contaminant is the strongly magnetic nickel ferrite. The iron oxides magnetite (strongly magnetic) and hematite (weakly magnetic) are the dominant corrosion products in BWRs. High-temperature EMF is seen as a means of reducing corrosion-product transport and activation and thereby reducing plant radiation fields.

Electromagnetic filtration

Various magnetic separation processes have been studied and developed over the past century. Most of the early activity was directed toward separating strongly magnetic materials from other materials, for example, ferrous ores from associated mineral contaminants. With the advent of efficient electromagnetic systems, this technology was adapted to more demanding separation processes, including power plant feedwater purification.

Magnetic filtration is the physical separation of magnetically susceptible particles from a liquid stream by magnetic forces. An electromagnetic filter consists of a pressure vessel with entrance and exit nozzles, a solenoid magnet that surrounds the vessel, and an internal matrix for shaping the magnetic field within the vessel (Figure 1). Many types of matrix elements have been used; the most common are $\frac{3}{16}$-in-diam balls and expanded metal mesh, both made of stainless steel alloys. During operation very intense magnetic field gradients are produced within the vessel matrix. The magnetized steel balls (or mesh) attract magnetically susceptible particles present in the process stream flowing through the filter. These particles are held on the surface of the balls until the magnetic field is removed; then they are flushed away as concentrated waste.

BWR application

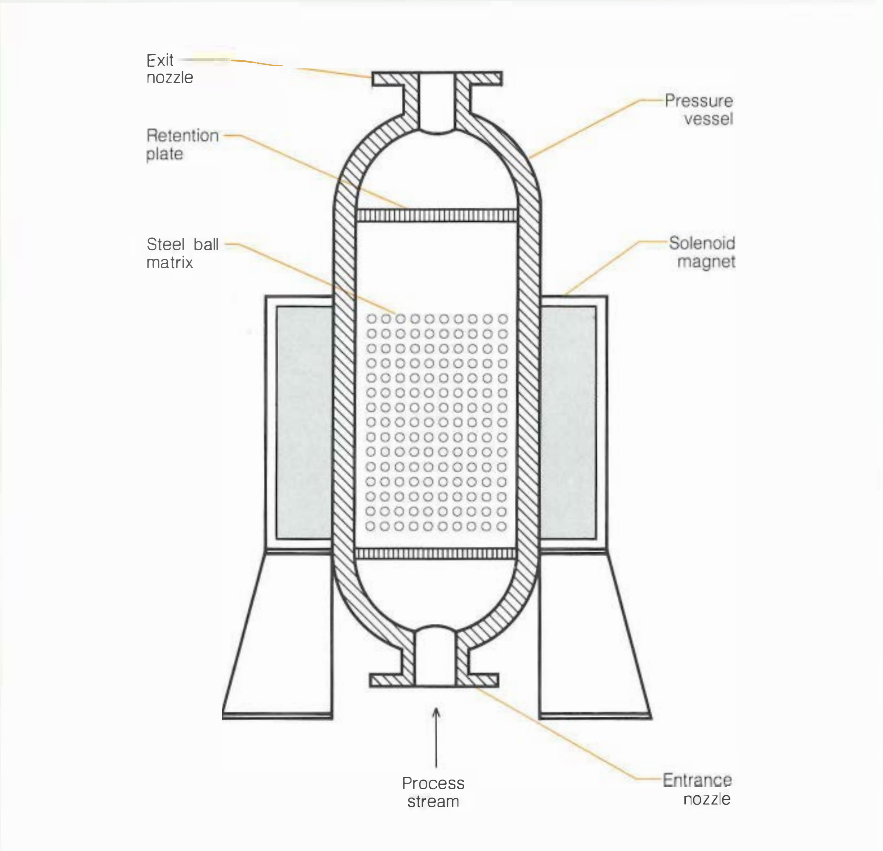
Research on radiation field buildup in BWRs has established a direct connection between the presence of iron oxides and the formation of the activation products cobalt-58 and cobalt-60 (*EPRI Journal*, October 1980, p. 51). Iron oxide seems to provide a residence site in the core for these materials. When released from the fuel surfaces, the activated materials may enter the corrosion film of the reactor coolant system. Three BWR process locations have been identified as most appropriate for high-temperature EMF—the reactor recirculating water, the final feedwater, and water from the forward-pumped heater drains. The last is preferred on the basis of iron contamination levels, the percentage of magnetite in the contamination, and required filter design flow rate.

Kraftwerk Union is assessing the performance of an EMF system installed at the Isar BWR plant in the Federal Republic of Germany (RP1445-3). This system, the only full-size one currently in operation at a nuclear power station, uses a feedwater tank (Figure 2). Water from the forward-pumped drains and condensate enter this tank on different sides of an internal baffle plate. The filter processes the water from the drains at 390 kg/s (6500 gal/min), delivering the purified stream to the other side of the tank. The EMF process rate is one-third of the final feedwater flow rate.

The filtration efficiency for iron at Isar was found to be approximately 60%. By comparison, an efficiency of 90% was achieved in EMF test work conducted by General Electric Co. at Carolina Power & Light Co.'s Brunswick nuclear station. The difference in performance is related to the iron species involved. At Isar magnetite, a strongly magnetic material, constitutes only a minor fraction of the iron contamination. Because iron removal varies directly with magnetite percentage, the efficiency of the Isar system was reduced. Magnetite percentage is an important consideration in assessing the applicability of EMF technology to a BWR process stream.

Also, the Isar results point to the need for overall corrosion-product control. The EMF system removed only about 25% of the cor-

Figure 1 Electromagnetic filter for the purification of liquid streams. During operation an intense magnetic field is produced within the steel ball matrix, and magnetically susceptible particles in the process stream are attracted to the surface of the balls and held there. EPRI is investigating the application of such filters to process streams in LWR power plants.



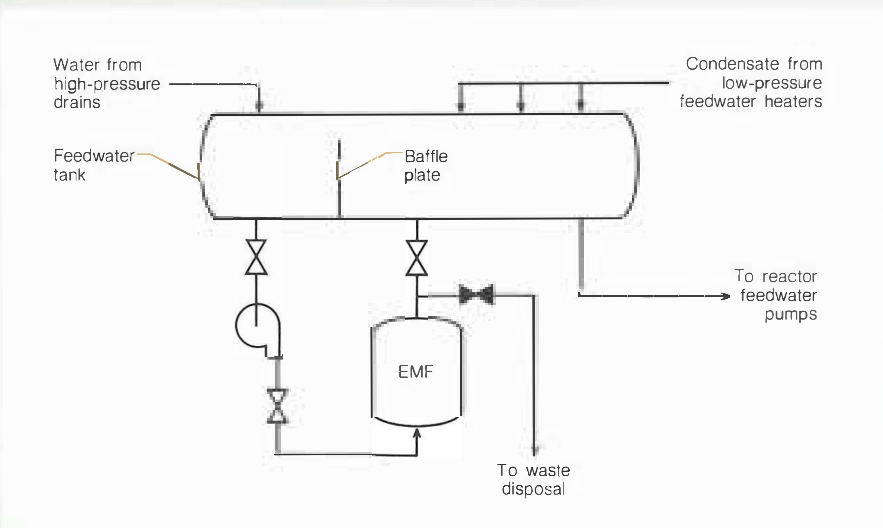


Figure 2 Electromagnetic filtration system at the Isar BWR power plant in the Federal Republic of Germany. Water from the high-pressure drains and condensate enter the feedwater tank on opposite sides of the baffle plate. The EMF unit processes the water from the drains and delivers it to the condensate side of the tank. The combined stream is then pumped to the reactor.

rosion products present in the condensate and feedwater streams. The major sources of these contaminants—those that ultimately control the iron input to the Isar reactor—are outside the Isar process stream.

PWR application

Presently, there are no PWR power plants designed for or operating with high-temperature EMF systems. EPRI is assessing the potential for PWR application in a project with Westinghouse Electric Corp. and Commonwealth Research Corp., a subsidiary of Commonwealth Edison Co. (RP1445-2, -5). The project involves developing a design for an EMF system for a PWR plant. A decision on proceeding with the EMF installation will be made at a later date. The process design and equipment layout have been completed, and EMF licensability has been reviewed.

As part of this effort, a mathematical model (CORA) and existing activity transport data are being used to assess the effectiveness of EMF for radiation field control in PWRs. The model predicts that EMF application would result in a radiation field reduction of greater than 50%. Although this analysis is the product of the best engineering judgment concerning activity transport in a PWR, the transport mechanisms are complex and are not completely understood. Therefore, determination of the actual impact of EMF on radiation fields must await a full-scale plant demonstration.

Whether or not to install the EMF system will be decided on the basis of results from the initial assessment phase of the project. *Project Manager: Michael D. Naughton*

LWR REACTIVITY CONTROL SYSTEMS

Control of the power level in the core of a nuclear reactor is maintained by the reactivity control system. A material capable of strongly absorbing thermal neutrons is used to make modest changes in the reactor power level while maintaining constant coolant temperature and pressure, and to promptly shut down (scram) the reactor if abnormal conditions arise. The reactivity control systems used in BWRs and PWRs are very different in design, and they have different performance records in commercial service. This report will review the designs and their performance and will describe EPRI's R&D activities relating to the systems. These projects, which are supported by the Nuclear Systems and Materials Department, address the materials performance of the systems rather than their neutronics capabilities.

Design

In a BWR, one cross-shaped control blade and four adjacent fuel assemblies compose the basic unit used to build up the reactor core. The control blades enter the core from the bottom. In the standard General Electric Co. design, each control blade contains 84 absorber tubes (21 in each wing of the cross) constructed of type-304 stainless steel. Each tube is filled with boron carbide (B_4C) powder, which is compacted to 65–70% of its theoretical density. Stainless steel balls are used to separate each tube into 18-inch-long compartments. These balls are held at the proper position by slight crimps in the tube. After being loaded with the B_4C powder, the tubes are welded shut on both ends. The individual tubes are designed to act as pressure vessels and to retain their integrity over the projected control blade lifetime. Each tube must contain the helium gas that can be released as a by-product when the boron captures a neutron, and it must resist other internally and externally applied stresses. The tubes are held in the cruciform array by a type-304 stainless steel sheath that extends their full length. Holes drilled in the sheath permit cooling of the absorber tubes by the primary coolant.

In a PWR, assemblies consisting of clusters of cylindrical absorber rods are used for reactivity control. These rods move within guide tubes in selected fuel assemblies. Above the core each cluster of absorber rods is attached to a spider connector and drive shaft, which is raised and lowered by a drive mechanism mounted on the reactor vessel head. Under scram conditions gravity causes the control rods to drop into the reactor core. The neutron-absorbing material is usually a silver-indium-cadmium alloy, which is encased in type-304 stainless steel rods. As in the BWR design, the function of these stainless steel rods is to isolate the absorber material from the reactor coolant.

Performance

Initial estimates placed the average lifetime of a BWR control blade at approximately 15 full-power years. This figure was based on an evaluation of two potentially life-limiting factors: loss of control effectiveness due to boron depletion (specifically, depletion of the ^{10}B isotope), and material degradation due to internal stress levels approaching the design limit. (The source of this internal stress is the release of the transmutation product helium from the B_4C powder.)

Recent evidence indicates that in addition to boron depletion, B_4C powder can be lost through cracks that form in the absorber tubes. Examinations of control blades suggest the following mechanisms lead to this B_4C loss. The B_4C particles swell under irradiation, filling the initial void volume. As this swelling continues, the expanding particles stress the absorber tube, resulting in stress levels that can exceed the yield stress of irradiated type-304 stainless steel. At such high stress levels and in the oxygenated water of the BWR core, the absorber tube becomes susceptible to intergranular stress corrosion cracking. Cracks initiate at the outer diameter of the tube and grow; eventually, through-wall penetration of the tube results. Failure of the tubing permits water to come in contact with the B_4C powder. The absence of B_4C observed in neutron radiographs of failed absorber tubes suggests that irradiated B_4C can be washed out by the coolant. The tubes most susceptible to failure and B_4C loss are the outer tubes at the top of the control blade, the region subjected to the highest neutron exposure.

Important materials performance considerations in determining lifetime limits for PWR control assemblies involve the ability of the irradiated type-304 stainless steel rods to withstand stresses imposed by swelling of the silver-indium-cadmium control material; to maintain their integrity under various mechanical loads (such as fatigue, creep, and wear resulting from contact with the surrounding control rod guide tubes); and to withstand the loss of wall thickness due to corrosion. Although estimates of design lifetimes are clearly dependent on plant-specific exposure levels, typical vendor estimates range from 10 to 15 years. The field performance of silver-indium-cadmium control rods has been outstanding. No rod failures have been attributed to the degradation of materials during in-reactor exposure. This record has provided little incentive to perform costly post-irradiation examinations. Accordingly, little nonproprietary information exists with which

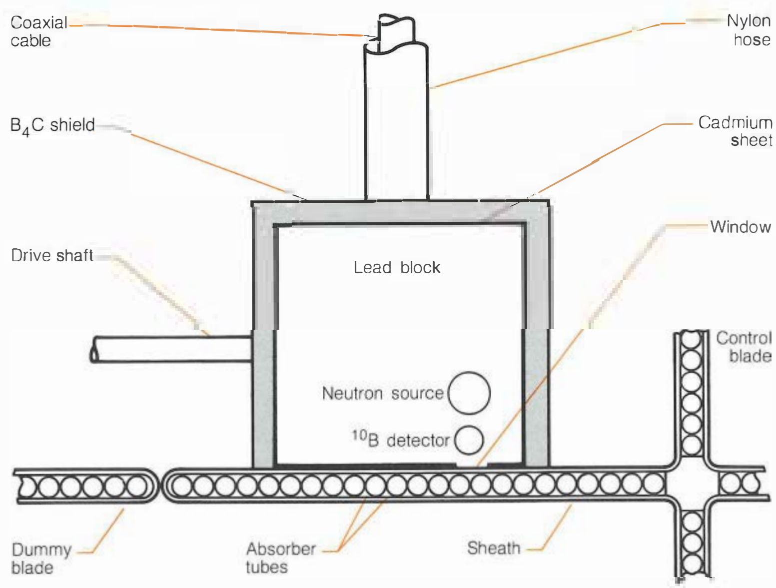


Figure 3 Cross-section view of a nondestructive inspection device developed to determine whether BWR control rods have lost their neutron-absorbing material (B_4C). As the device is driven across a control blade wing in a fuel storage pool, fast neutrons from the ^{252}Cf source pass through the equipment and the blade wing and are thermalized in the water. Both the B_4C shield and the cadmium sheet bounding the lead block are neutron absorbers; thus the thermalized neutrons can reach the detector only by passing back through the control blade wing in the area of the window in the cadmium sheet. If the blade's absorber tubes have retained their B_4C, few neutrons will reach the detector; if the tubes have lost B_4C, the detector's signal will be larger. The dummy blade prevents an artifactual increase in the signal as the device scans the outer part of each wing.

to evaluate the accuracy of the lifetime estimates. The field experience does suggest the possibility of extended use for this component.

R&D efforts

In view of the licensing implications arising from the loss of B_4C from failed BWR absorber tubes, NRC required each utility to provide pertinent information based on a detailed destructive examination of its highest-rated blade. Such examinations are very expensive, and only a few blades can be examined in detail in a hot cell. Therefore, EPRI has supported the development of a nondestructive technique that can be used in a fuel storage pool to determine quickly, and for a statistically significant number of blades, whether B_4C is present or missing. National Nuclear Corp. was contracted to develop and test equipment with such capabilities (RP1628-1).

The equipment (Figure 3) consists of a neutron source (^{252}Cf) and a ^{10}B proportional counter, which are encased in a lead block. This block is surrounded by a neutron-absorbing cadmium sheet that has a narrow hole (window) on the side facing the control blade. The block also has an outer shield of neutron-absorbing B_4C on the three sides that are away from the control blade. The apparatus is used under water and is driven at constant speed across a control blade wing.

Fast neutrons from the source pass freely through the equipment and the control blade wing being inspected and are then thermalized (slowed down) in the water. Once thermalized, neutrons can reach the detector only if they pass through the area of the blade adjacent to the window in the cadmium sheet. Other thermalized neutrons will be absorbed by the sheet or the B_4C shield. Because B_4C is an effective absorber of thermalized neutrons, only a few counts will be registered by the proportional counter if the area of the control blade adjacent to the window contains B_4C. If the B_4C has been lost, the thermalized neutrons will readily pass through the absorber tube, the blade sheath, and the window to reach the detector, resulting in a large signal.

Measurements were initially made on 24 control blades exposed at the Monticello reactor of Northern States Power Co. The nondestructive examination indicated that B_4C had been lost from the top 30 inches of the outermost tube of the most highly exposed blade; it also indicated a slight possibility that B_4C had been lost from the top of the next innermost tube.

Ten absorber tubes from this blade were shipped to the hot cells at General Electric's Vallecitos Nuclear Center for measurements designed to confirm the capabilities of the nondestructive inspection device. According to the results of neutron radiography performed there, the outermost tube lost B_4C from the top 33 inches, and the other tubes had suffered no loss of B_4C. The agreement between the nondestructive and destructive examination results is encouraging. Additional measurements have recently been performed on control blades exposed in Commonwealth Edison's Dresden-2 reactor, and others will be made later this year at Mohawk Power Corp.'s Nine Mile Point reactor.

In the area of PWR control rod performance, EPRI is negotiating projects with The S. M. Stoller Corp. and Westinghouse to develop data and analytic methods for deriving realistic estimates of the lifetime of materials used to contain the neutron-absorbing silver-indium-cadmium alloy. The objective is to obtain measurements, over several irradiation cycles, of those phenomena most likely to limit control rod performance. Because the measurements will probably be obtained over a range of exposures at which the control rods will have suffered little or only modest degradation, the development of analytic methods permitting extrapolation of the data to higher exposures is required. This approach should eventually enable utilities to plan replacement of PWR control rods on a firmer technical basis than is currently available to them. *Project Manager: Howard Ocken*

New Contracts

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
Advanced Power Systems				
RP1663-2	Evaluation of Advanced-Fuel Power Plant Characteristics	1 month	40.0	Public Service Electric & Gas Co. *N. Amherd*
RP1971-1	Evaluation of Internal Confinement Engineering Opportunities on Existing and Planned Facilities	9 months	118.8	Westinghouse Electric Corp. *K. Billman*
RP1996-1	Performance Assessment: Large Wind Turbine	1 year	199.2	Arthur D. Little, Inc. *F. Goodman*
RP2110-1	Improved Distillate Yields From Liquefaction of Subbituminous Coal	4 months	150.3	University of Wyoming *N. Stewart*
Coal Combustion Systems				
RP1456-2	High-Intensity Ionizer, 1-MW Performance Test	8 months	189.1	Southern Research Institute *D. Giovanni*
RP1649-8	Recommended Design Guidelines for Draft Fans in Large Power Generating Units	20 months	64.0	Fan Systems Co. *I. Diaz-Tous*
RP1651-5	Air/Gas System Dynamics of Fossil Fuel Power Plants	21 months	315.0	Massachusetts Institute of Technology *I. Diaz-Tous*
RP1689-9	Macrofouling Control Methods	1 year	177.5	Stone & Webster Engineering Corp. *I. Diaz-Tous*
RP1854-1	On-Line Monitoring of Turbine Blades for Incipient Failure Detection	1 year	104.9	Franklin Research Center *A. Armor*
RP1957-1	Eddy-Current NDE for In-Service Inspection of Turbine Generators	3 years	442.5	General Electric Co. *A. Armor*
Electrical Systems				
RP1764-4	Probabilistic Approach to Stability Analysis	13 months	49.9	Arizona State University *N. Balu*
RP1764-6	Specification of Computer-Aided Design of Transmission Protection Systems	19 months	50.0	University of Washington *J. Mitsche*
RP1764-8	Selective Modal Analysis in Power Systems	1 year	49.9	Massachusetts Institute of Technology *N. Balu*
RP1903-1	Advanced HVDC Insulator Design	38 months	401.7	University of Southern California *J. Dunlap*
RP1964-1	Reference Manual: Methodology for Integration of HVDC Links in Large AC Systems, Phase 1	13 months	10.0	Ebasco Services, Inc. *N. Balu*
RP2028-2	PCB Removal From Transformers	11 months	147.7	The Franklin Institute *G. Addis*
RP7891-1	Morphologic Study of Extruded Dielectric Cable Materials	35 months	80.0	University of Utah *B. Bernstein*
Energy Analysis and Environment				
RP1145-6	Scoping Study: Regional Electric Vehicle Market Demand and Related Impact Assessment Methodologies	7 months	50.0	General Research Corp. *J. Wharton*
RP1369-2	Nitrogen Oxide Transformation in Power Plant Plumes	2 years	261.4	Battelle, Columbus Laboratories *G. Hilst*
RP1613-6	Transfer of Electricity Supply Model to Industry	7 months	75.0	Decision Focus, Inc. *V. Niemeyer*
RP1808-1	Probabilistic Simulation for Load Duration Curves With Energy Storage	1 year	53.5	Ohio University *J. Delson*
RP1826-2	Investigation of the Validity for Dose-Response Modeling of in Vitro and in Vivo Tests	8 months	30.0	University of California *P. Ricci*
RP2040-1	R&D Planning: Application of Analytic Methods	15 months	229.9	Applied Decision Analysis, Inc. *S. Sussman*

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager

Energy Management and Utilization

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP1041-8	Preliminary Evaluation: Phosphoric Acid (FCG-1) Fuel Cell Power Plant Integrated With a Coal Gasifier	7 months	71.4	Kinetics Technology International, Inc. *B. Mehta*
RP1085-8	Investigation of Layered Structure for Carbonate Fuel Cells	15 months	308.3	General Electric Co. *J. Appleby*
RP1086-7	Testing and Evaluation of Solid-Polymer-Electrolyte Water Electrolyzer for On-Site Production of Hydrogen for Generator Cooling Application	29 months	36.0	PSE&G Research Corp. *B. Mehta*
RP1199-15	Assessment of the Commercial Potential for CAES System	8 months	78.9	Decision Focus, Inc. *R. Schainker*
RP1201-20	Concept Study: Distributed-Logic Load Management Control System	3 months	50.0	Honeywell Control Systems *T. Lechner*
RP1276-9	Evaluation of Dual Energy Use Systems Cogeneration Systems Design and Analysis—Enhanced Oil Recovery	16 months	224.2	RMR Associates *S. Hu*
RP1569-2	Utility Planning Guide, Electric Vehicle Demonstration	5 months	57.5	Booze, Allen & Hamilton, Inc. *J. Mader*
RP1791-2	Compressed-Air Energy Storage: Two-Phase Flow Instability and Control Analysis	11 months	150.0	United Technologies Research Center *R. Schainker*
RP1791-3	High-Pressure Field Tests	1 year	95.0	Société Electrique de l'Our S.A. *R. Schainker*
RP1791-4	Near-Term Compressed-Air Energy Storage—Waste Heat Recovery Systems Analysis	4 months	44.5	Reynolds, Smith & Hills, Inc. *R. Schainker*
RP1791-5	Recuperative Heat Exchangers in Compressed-Air Energy Storage	9 months	97.4	Encotech, Inc. *R. Schainker, H. Stringer*
RP1832-1	System Analysis of Energy Storage Options	6 months	81.7	Decision Focus, Inc. *T. Yau*
RP1965-1	Validation of Industrial Energy Data Bases	15 months	125.0	Synergic Resources Corp. *I. Harry*

Nuclear Power

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP443-3	Two-Phase Flow Interactions in Reactor Components	11 months	156.0	Dartmouth College *B. Sun*
RP964-8	Seismic Evaluation of Multiple Support Piping System	9 months	90.0	University of California at Berkeley *Y. Tang*
RP1074-3	Guidelines: Software Development and Maintenance	4 months	5.0	Science Applications, Inc. *O. Ozer*
RP1160-2	Regime Transitions, Heat Transfer, and Stability in Reflux Condensation and Natural Circulation	1 year	62.9	University of California at Santa Barbara *M. Toren*
RP1160-3	Fluid Property and Noncondensible Gas Effects on the Reflux Condensation Heat Transfer in a Closed Tube	1 year	48.8	University of California at Berkeley *M. Toren*
RP1163-4	Nuclear Modular Modeling	9 months	68.1	Boeing Computer Services, Inc. *J. Sursock*
RP1233-8	Development of Recommended Procedures for Seismic Risk Analysis of Nuclear Power Plants	8 months	50.0	Structural Mechanics Associates *I. Wall*
RP1246-2	Acoustic Monitoring of Nuclear Safety and Relief Valves	8 months	233.6	Babcock & Wilcox Co. *H. Shugars*
RP1320-3	LWR Sensitivity Analysis Using Advanced RETRAN Models	7 months	50.6	EDS Nuclear, Inc. *L. Agee*
RP1332-2	BWR Materials Performance During Startup	8 months	499.8	General Electric Co. *M. Fox*
RP1384-2	BWR Void Prediction Models	1 year	119.6	University of Washington *L. Agee*

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP1391-3	Decentralized Data Systems Survey Recommendations	6 months	96.7	Southwest Research Institute *J. Huzdovich*
RP1542-1	Program Plan: Structural Reliability Methodology	6 months	65.0	Pickard, Lowe and Garrick, Inc. *S. Tagart*
RP1543-3	Reliability of Piping and Fittings	7 months	16.4	Swanson Service Corp. *R. Nickell*
RP1550-2	Enhancement of Time-Integration Procedures in ABAQUS–ND	11 months	70.0	Lockheed Missiles and Space Co., Inc. *H. Tang*
RP1555-1	Fuel Performance Data Base Support	3 years	498.8	S. Levy, Inc. *T. Oldberg*
RP1556-1	Failure Analysis: Main Coolant Pump Shaft Seal	13 months	179.3	Energy Systems Development Center *M. Kolar*
RP1556-2	Plan for Improved Nuclear Main Coolant Pump Reliability	6 months	64.9	University of Virginia *R. Swanson*
RP1756-4	Specimen Retrieval, Shippingport Power Plant	1 year	24.8	International Energy Associates, Ltd. *T. Marston*
RP1760-3	Combined Convection and Radiation Heat Transfer Under Conditions Simulating Uncovered Reactor	18 months	51.5	Purdue Research Foundation *B. Sun*
RP1761-4	Reload Safety Analysis Methodology: Task D, Uncertainty Analysis	8 months	197.0	Combustion Engineering, Inc. *R. Lee*
RP1842-2	Full-Scale Probabilistic Safety and Availability Analysis, Sequoyah Nuclear Plant	25 months	50.0	Tennessee Valley Authority *B. Chu*
RP1842-3	Comparison of MARCH/CORRAL and KESS/RSYST Consequence Evaluation Methodologies With Applications to Sequoyah RPA Study	7 months	180.7	Science Applications, Inc. *B. Chu*
RP1927-1	Data Base for Flow-Through Junctions and Breaks	1 year	39.0	University of California at Santa Barbara *L. Agee*
RP1929-7	Effects of Impurity Segregation on Stress Corrosion Cracking of Low-Alloy Steels	1 year	84.3	General Electric Co. *A. Giannuzzi*
RP1929-8	Microkinetics of Stress Corrosion Cracking in Steam Turbine Disk Alloys, Phase 1	7 months	60.6	SRI International *A. Giannuzzi*
RP1930-1	Hydrogen Water Chemistry for BWRs	2 years	999.5	General Electric Co. *M. Fox*
RP1932-8	Hydrogen Mixing and Distribution in Containment Atmosphere	8 months	257.2	U.S. Department of Energy *L. Thompson*
RP1932-10	Modeling and Analysis of Hydrogen Combustion	9 months	70.4	Factory Mutual Research Corp. *L. Thompson*
RP1937-1	Cable Tray Support System With Planned Damping	2 years	227.8	Duke Power Co. *C. Chan*
RP1943-1	Assessment of BWR Channel Lifetimes	6 months	49.6	Dominion Engineering *H. Ocken*
RP2031-1	Scoping Study: Comparative Risk Assessment Between LWRs and LMFBRs	14 months	159.0	Science Applications, Inc. *A. Adamantiades*
RP2055-01	Integrity of LWR Component Supports	8 months	28.7	EDS Nuclear, Inc. *T. Marston*
RP2056-1	Thermal Analysis of TMI-2 Pressure Boundary	7 months	70.0	General Electric Co. *S. Tagart*
RP2062-1	Review of Proposed Dry Storage Systems	4 months	28.4	S. Levy, Inc. *R. Williams*
RP2063-1	Low-Level Waste Disposal Site Selection	10 months	152.4	Rogers & Associates Engineering Corp. *R. Williams*
RP2063-2	Low-Level Waste Disposal, Illustrative Criteria and Safety Analysis	9 months	183.7	Analytic Sciences Corp. *R. Williams*

Research and Development

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP1876-1	Retaining Ring Alloy Evaluation and Demonstration, Phase 1	19 months	711.4	General Electric Co. *R. Viswanathan*

New Technical Reports

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

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

Requests for copies of specific reports should be directed to Research Reports Center, P.O. Box 50490, Palo Alto, California 94303; (415) 965-4081. There is no charge for reports requested by EPRI member utilities, government agencies (federal, state, local), or foreign organizations with which EPRI has an agreement for exchange of information. Others in the United States, Mexico, and Canada pay the listed price. Research Reports Center will send a catalog and complete price list (including foreign prices) on request.

Standing orders for free copies of reports in EPRI program areas or Technical Summaries of reports for each EPRI technical division may be placed by EPRI member utilities, libraries of U.S. federal, state, and local government agencies, and the official representative of any foreign organization with which EPRI has an information exchange agreement. For details, write to EPRI Technical Information Division, P.O. Box 10412, Palo Alto, California 94303.

Microfiche copies are available from National Technical Information Service, P.O. Box 1553, Springfield, Virginia 22151.

ADVANCED POWER SYSTEMS

Coal Devolatilization Information for Reactor Modeling

AP-1803 Final Report (RP986-5); $23.00

Experimental research on coal devolatilization was surveyed for information needed in modeling coal gasifiers. The capabilities of existing experimental apparatus were also identified, and a research program was formulated to fill the information gaps found in the survey. The focus was on the British Gas Corp.–Lurgi, Texaco, and Combustion Engineering gasifiers; conceptual descriptions of devolatilization phenomena occurring in each gasifier served as the basis for the literature and apparatus survey. The contractor is the Massachusetts Institute of Technology. *EPRI Project Manager: G. H. Quentin*

Load-Change Testing of a Large Commercial Oxygen Plant

AP-1824 Final Report (RP1806-1); $8.00

This report presents the results of tests conducted to demonstrate the dynamic response capabilities of a commercial oxygen plant. The tests covered a wide range of load-changing maneuvers that might typically be encountered by coal gasification–combined-cycle power plants in load-following service. The report describes the air separation process used and discusses the project's success in establishing the suitability of commercial oxygen plants for load-following service without the need for liquid oxygen storage facilities. The contractor is Air Products and Chemicals, Inc. *EPRI Project Manager: G. H. Quentin*

Open-Cycle MHD Technology Status and Development Perspective: Operational Analysis

AP-1864 Topical Report (RP639-1); $8.00

This report examines technical and economic issues related to open-cycle magnetohydrodynamic (MHD) power plant development. It describes open-cycle MHD processes, evaluates MHD's potential and economic risk, and summarizes development efforts and technical barriers. The status of each key technology is reviewed and its development path indicated. The contractor is Westinghouse Electric Corp. *EPRI Project Manager: P. S. Zygielbaum*

Conference Proceedings: Synthetic Fuels, Status and Directions

WS-79-238 Conference Proceedings; Vol. 1, $30.50; Vol. 2, $33.50

Papers given at a conference on synthetic fuels cosponsored by EPRI and the West German Federal Ministry for Research and Technology are presented. The conference was held in October 1980 in San Francisco. Volume 1 presents an introduction, a policy statement, and papers on the production of liquid fuels from coal and shale oil. Volume 2 covers clean gaseous fuels and power generation as they relate to the production of synthetic fuels. *EPRI Project Manager: S. B. Alpert*

COAL COMBUSTION SYSTEMS

Utility-Oriented Approach for Root Cause Analysis of Power Plant Equipment Problems

CS-1832 Final Report (RP1265-2); $8.00

The development of a preliminary utility-oriented approach for performing root cause analyses of power plant equipment problems is described. The four basic elements of a root cause analysis program are development of an information system to provide data, formation of a skilled investigative team with a proper mix of technical disciplines and management support, use of a logic diagram approach to isolate the root cause, and formal presentation of results and recommended corrective action. The contractor is Science Applications, Inc. *EPRI Project Manager: J. B. Parkes*

Methodology for Determining the Impact of Environmental Regulatory Programs

CS-1834 Final Report (TPS79-743); $14.00

A systematic review of existing and future major federal environmental legislation and regulatory programs affecting air, water, land, and solid-waste management was undertaken to ensure that environmental licensing constraints and potential regulatory impacts on the development and commercialization of advanced coal conversion technologies can be recognized, assessed, and planned for. The development and application of a methodology for assessing environmental impacts and identifying potential problem areas are described. The contractor is Fred C. Hart Associates, Inc. *EPRI Project Manager: D. M. Golden*

EPRI Condenser-Related Research Projects

CS-1841-SR Special Report; $9.50

This report summarizes research projects funded by EPRI through 1981 involving steam surface condensers in electric power plants. It contains sections on the identification of condenser failure causes, air and water inleakage control, erosion-corrosion control, leak detection, biofouling and scaling, engineering design, nondestructive evaluation techniques, and special issues related to closed-cycle cooling systems. *EPRI Project Manager: I. A. Diaz-Tous*

Cyclic Reheat for FGD: Status Report

CS-1843 Final Report (RP1652-1); $12.50

This report presents a technical and economic evaluation of cyclic reheat for flue gas desulfurization systems, as well as the results of field tests at the only U.S. plant with a full-scale cyclic reheat system—Southwestern Public Service Co.'s Harrington station. Three conventional reheat systems (in-line steam, hot air injection, and oil-fired reheat) were evaluated and compared with the Harrington liquid-coupled heat exchange approach for both low- and high-sulfur cases. The contractor is Bechtel National, Inc. *EPRI Project Manager: R. G. Rhudy*

Predictions of Combustion Turbine Performance in Pressurized Fluidized-Bed Combustion Power Plants

CS-1845 Final Report (RP1336-1); $14.00

This report predicts the erosion, deposition, and corrosion behavior of utility gas turbines operating on pressurized fluidized-bed combustion (PFBC) flue gas. The turbine performance predictions are based on mathematical models; inputted to the models were test results from erosion, deposition, and corrosion experiments. Turbine design modifications required to increase tolerance to PFBC flue gas are summarized. The contractor is Westinghouse Electric Corp. *EPRI Project Managers: S. G. Drenker and W. W. Slaughter*

Evaluation of Ceramic Fiber Filters for Hot Gas Cleanup in Pressurized Fluidized-Bed Combustion Power Plants

CS-1846 Topical Report (RP1336-1); $9.50

The results of high-temperature and high-pressure testing of two ceramic baghouse filters for hot gas cleanup in pressurized fluidized-bed combustion power plants are given. The test facility and the filter units are described, particulate sampling is summarized, and particulate removal performance is detailed. Recommendations for further development work are included. The contractor is Westinghouse Electric Corp. *EPRI Project Managers: S. G. Drenker, W. W. Slaughter, and O. J. Tassicker*

Calcium-Based Sorbent Desulfurization in Pressurized Fluidized-Bed Combustion Power Plants

CS-1847 Topical Report (RP1336-1); $14.00

The high-pressure sulfur-capture behavior of 11 limestones, dolomites, and regenerable sorbents was examined. Sorbent performance was measured in a pressurized thermogravimetric analyzer in the range of 16–20 atm. Mathematical models were used to predict sorbent requirements and performance in pressurized fluidized-bed combustor-boilers at 16 and 20 atm. The contractor is Westinghouse Electric Corp. *EPRI Project Managers: S. G. Drenker and W. W. Slaughter*

Materials Problems in Fluidized-Bed Combustion Systems
CS-1853 Final Report (RP979-1); $26.00

As part of work on materials degradation processes in fluidized-bed combustion systems, the effects of a number of operating variables on the in-bed sulfidation-oxidation corrosion of alloys have been examined. This report presents a review of available data and discusses attempts to measure local oxygen activity by using an electrochemical probe. It also presents results from three 250-h tests that examined the effects of excess air levels, coal type, and the use of dolomite as the sulfur sorbent. (The results of previous tests are reported in CS-1475.) The contractor is the National Coal Board. *EPRI Project Manager: John Stringer*

Proceedings of the Joint Symposium on Stationary Combustion NO_x Control
WS-79-220 Symposium Proceedings; Vol. 1, $42.50; Vol. 2, $27.50

The Joint Symposium on Stationary Combustion NO_x Control, held in October 1980 in Denver, consisted of over 50 presentations describing recent advances in NO_x control technology, including applications for pulverized-coal-fired utility boilers. Volume 1 contains papers on the regulatory aspects of NO_x emissions and NO_x control through burner design and combustion modification. Volume 2 contains papers on postcombustion control (flue gas treatment) and the characterization of NO_x and other combustion-generated emissions. *EPRI Project Manager: J. E. Cichanowicz*

ELECTRICAL SYSTEMS

Field Demonstrations of Communications Systems for Distribution Automation
EL-1860 Final Report (RP850); Vol. 1, $17.00; Vol. 2, $20.00; Vol. 3, $24.50; Vol. 4, $29.00

Volume 1 summarizes the results of a program jointly sponsored by EPRI and DOE to develop and test communication systems for distribution automation and load management. The program included three power line carrier (PLC) projects, a UHF radio project, and a telephone project. For each project a two-way (half-duplex) digital communication system was developed to perform such functions as fault location and isolation, distribution feeder switching, load control, time-of-day metering, remote meter reading, and equipment monitoring. Volumes 2 and 3 detail two of the PLC projects, and Volume 4 the UHF radio project. The contractors are V. T. Rhyne, Brown Boveri Compuguard Corp., Carolina Power & Light Co., Westinghouse Electric Corp., Detroit Edison Co., and Long Island Lighting Co. *EPRI Project Manager: W. E. Blair*

Broadcast Radio System for Distribution Communications
EL-1868 Final Report (RP1535-1); $11.00

This report describes the development and testing of a prototype bidirectional radio communication system for load management and distribution automation. The system's forward (control) link uses a standard AM broadcast channel; the return (data) link uses a VHF channel assigned for utility communications. System design, hardware design and fabrication, and field testing at a 1070-kHz, 50-kW radio station in Los Angeles are detailed. The contractor is Altran Electronics, Inc. *EPRI Project Manager: W. E. Blair*

Free and Forced Convective Cooling of Pipe-Type Electric Cables
EL-1872 Final Report (RP7853-1); Vol. 1, $21.50; Vol. 2, $9.50

Several aspects of free and forced convective cooling of underground electric cable systems were investigated. Volume 1 discusses the fluid dynamic and thermal aspects of various components of the cable system. Volume 2 presents a feasibility study of a novel electrohydrodynamic pump concept involving the use of a traveling electric field to move dielectric oil in a cable system. The contractor is the University of Illinois at Urbana-Champaign. *EPRI Project Manager: T. J. Rodenbaugh*

ENERGY ANALYSIS AND ENVIRONMENT

Characterization of Acidic Precipitation in the Adirondack Region
EA-1826 Final Report (RP1155-1); $17.00

Atmospheric inputs into three lake watersheds in the Adirondack Mountains of New York were quantified for the period May 1978 to August 1979. Rain and snow samples were analyzed for pH, conductivity, SO_4, NO_3, Cl, NH_4, Ca, Mg, K, and Na. The quantity and quality of precipitation were found to be similar for the three watersheds on a monthly and an annual basis, but individual events would occasionally result in wide fluctuations across the network. The contractor is Rensselaer Polytechnic Institute. *EPRI Project Managers: John Jansen and Charles Hakkarinen*

Literature Review: Response of Fish to Thermal Discharges
EA-1840 Final Report (RP877); $11.00

This review of literature on the responses of fish species to thermal discharges was prepared from information contained in the EPRI Cooling System Effects Data Base. Tables of field and laboratory data on selected temperature variables for some 60 fish species are presented. Where possible, comparisons between field and laboratory observations are made. The contractor is Oak Ridge National Laboratory. *EPRI Project Manager: I. P. Murarka*

The Problem of "Second Best" and the Efficient Pricing of Electricity
EA-1852-SR Special Report; $6.50

This report examines the feasibility and potential usefulness of extending the economic welfare theory of "second best" to electricity pricing. This theory deals with issues of resource allocation and pricing in situations where some products are not priced at marginal cost. The contractor is M. Bruce Johnson. *EPRI Project Managers: J. Boyd and S. D. Braithwait*

Impingement and Entrainment: An Updated Annotated Bibliography
EA-1855 Final Report (RP877); $24.50

The computer-searchable EPRI Cooling System Effects Data Base contains over 11,000 annotated references. This annotated bibliography presents 1343 references dealing with entrainment and impingement effects of cooling systems on aquatic organisms. The references were obtained from the open literature and from environmental reports and impact statements for electric power plants; the update contains literature added since 1978. The contractors are Atomic Industrial Forum, Inc., and Oak Ridge National Laboratory. *EPRI Project Manager: I. P. Murarka*

ENERGY MANAGEMENT AND UTILIZATION

Solar Heating and Cooling (SHAC) Simulation Programs: Assessment and Evaluation
EM-1866 Final Report (RP1269-1); Vol. 1, $6.50; Vol. 2, $20.00

Computer programs available for use by utilities in simulating solar heating and cooling systems were identified, analyzed, tested, and evaluated. The documentation manuals of 11 programs were reviewed, and 4 programs were tested against benchmark cases in three building categories. Volume 1 summarizes the project results, and Volume 2 presents them in detail. The contractor is Arthur D. Little, Inc. *EPRI Project Manager: G. G. Purcell*

Reliability of Modularized Energy Storage Systems
EM-1890 Interim Report (RP370-17); $17.00

This report examines the reliability of modularized energy storage systems and summarizes performance measures, including (1) the time to first failure of the system, (2) the time between successive system failures, (3) available capacity, and (4) the number of module replacements over the planned system lifetime. The effect of module aging (under the assumption of a family of monotone failure rate distributions) and the effectiveness of periodic replacement are also discussed. The contractor is Science Applications, Inc. *EPRI Project Manager: W. C. Spindler*

NUCLEAR POWER

Shutdown Operational Techniques for Radiation Control in PWR Plants
NP-859 Final Report (RP825-2); $15.50

This report describes one phase of a PWR radiation control project—specifically, the research conducted on the cooldown-shutdown process. Refueling-shutdown test results that compare releases of cobalt-58 with and without the addition of hydrogen peroxide are presented. The contractor is Westinghouse Electric Corp. *EPRI Project Manager: R. A. Shaw*

Plant Decontamination Methods Review

NP-1168 Final Report (TPS78-816); $14.00

This report reviews the decontamination techniques currently employed at nuclear power plants, as well as the R&D being performed in this field by private and government laboratories. The planning and preparation necessary for a decontamination are discussed, and details are provided on equipment availability, radioactive waste generation, plant compatibility, and storage capacity. A brief description of corrosion film generation, transportation, activation, and deposition is included. The contractor is Babcock & Wilcox Co. *EPRI Project Manager: R. A. Shaw*

Analysis of the FLECHT SEASET Unblocked-Bundle Steam-Cooling and Boiloff Tests

NP-1460 Topical Report (RP959-1); $12.50

Forced-convection steam-cooling tests at low Reynolds numbers (simulated by means of the COBRA-IV-I computer code) and bundle boiloff tests were conducted in the unblocked-bundle task of the PWR FLECHT SEASET program. This report summarizes the analysis of the results, the development of a steady-state forced-convection steam-cooling heat transfer correlation, and comparisons of test data with the Yeh void fracture model. The contractor is Westinghouse Electric Corp. *EPRI Project Manager: K. H. Sun*

Defect Characterization by Acoustic Holography: Effects of Cladding on AH Imaging and Test-Block Results

NP-1534 Final Report, Vol. 2 (RP605-1); $12.50

As part of a study to expand the data base on the application of acoustic holography to heavy-section inspections, inspections of a specially prepared, partly clad test block were conducted. This volume summarizes the test results and presents limited comparisons between these results and destructive test results. Conclusions and recommendations are included. The contractors are Coe Associates (now Coecorp) and Babcock & Wilcox Co. *EPRI Project Manager: G. J. Dau*

Verification of Fault Tree Analysis

NP-1570 Key Phase Report (RP1233); Vol. 1, $14.00; Vol. 2, $14.00

Volume 1 describes the development of the EPRI Reliability and Maintainability Analyzer (ERMA), an electronic instrument for simulating the reliability of complex systems. The volume covers the operational concepts of ERMA, verification of its statistical behavior, and applications to system models of varying complexity. It also compares ERMA simulation results with results from fault tree codes using equivalent system models. Volume 2 details the design and construction of ERMA, including its electronic circuitry and supporting software. The contractor is Science Applications, Inc. *EPRI Project Managers: P. G. Bailey and G. S. Lellouche*

Corrosion and Corrosion Cracking of Materials for Water-Cooled Reactors

NP-1741 Final Report (RP311-1); $17.00

To evaluate corrosion and corrosion cracking in LWR systems, metallurgical tests were applied to the major alloys used in LWR piping, steam generators, and turbines. Various combinations of alloy, stress level, and water impurity and oxygen content were examined in extensive sets of accelerated tests. The contractor is Ohio State University. *EPRI Project Manager: T. O. Passell*

Current Perspectives in Nuclear Safety R&D

NP-1828-SR Special Report; $6.50

This report, originally presented as a paper at the Water Reactor Safety Research Information Meeting in October 1980, summarizes the general guidelines and major themes of nuclear safety research at EPRI. It covers recent advances and current efforts in organizational and plant data collection, scaled thermal-hydraulic tests, large-scale demonstrations, accident evaluation and consequence assessment, safety quantification, and assistance for nuclear plant control room operators. *EPRI Project Managers: W. B. Loewenstein and A. G. Adamantiades*

Chemical Cleaning Demonstration Test No. 1 on a Mock-up Steam Generator

NP-1829 Topical Report (RPS127); $9.50

This report describes work on a process to chemically remove corrosion products from the secondary side of PWR steam generators without causing excessive damage to the construction materials. The laboratory development of a solvent system and application techniques for removing corrosion products at temperatures below 200°F is reviewed, and the results of benchmark testing of one process in a mock-up steam generator are summarized. The contractor is Babcock & Wilcox Co. *EPRI Project Manager: C. S. Welty, Jr.*

BIGIF Fracture Mechanics Code for Structures: Introduction and Theoretical Background

NP-1830 Key Phase Report (RP700-5); $6.50

This report presents a general description of the current version of BIGIF, a computer program designed to calculate crack growth in a flawed structure. It summarizes the program's present capabilities and includes enough information to enable a decision about whether or not to use BIGIF. The contractor is Failure Analysis Associates. *EPRI Project Manager: M. J. Kolar*

Development of Electro-optical Instrumentation for Annular Two-Phase Flow Studies

NP-1831 Topical Report (RP1379-1); $12.50

This report describes the development of electro-optical instrumentation for studying annular two-phase flow regimes. It gives a general description of the system and discusses image recording of water droplets, droplet size and velocity distribution analysis, and improvement in liquid-phase thickness measurements. Pertinent optical, mechanical, and electronic system components are described in detail, and calibration charts and experimental data are presented. The contractor is Lawrence Berkeley Laboratory. *EPRI Project Managers: S. P. Kalra and J. P. Sursock*

Technical Feasibility of a PWR Design With a Low Water Volume Fraction Lattice

NP-1833 Final Report (RP1128); $12.50

This report examines the technical feasibility of using a UO_2-PuO_2 core with a very low water volume fraction in an Oconee-type PWR. Studies that addressed core reactivity control, thermal-hydraulic behavior, and response to a loss-of-coolant accident are described. On the basis of the analyses performed, the use of a tight-lattice core in a PWR appears, in principle, to be technically feasible. The contractor is Babcock & Wilcox Co. *EPRI Project Managers: A. G. Adamantiades and B. R. Sehgal*

Dynamic Thermal-Hydraulic Behavior of PWR U-Tube Steam Generators: Simulation Experiments and Analysis

NP-1837-SR Special Report; $11.00

This report describes an experimental and analytic study of U-tube steam generator behavior under normal and off-normal conditions. It describes (1) steady-state experiments involving system behavior, natural circulation processes, and overall heat transfer characteristics; (2) transient experiments simulating loss of feed and steam line break accident conditions; and (3) an analysis using a three-dimensional code. The state of the art of thermal-hydraulic modeling is also reviewed. *EPRI Project Manager: S. P. Kalra*

BWR Off-Gas Systems: Operating Experience and Planning Study

NP-1839 Final Report (TPS78-796); $15.50

Operating problems encountered with BWR off-gas systems, particularly systems augmented to catalytically recombine hydrogen and oxygen, are investigated. Special emphasis is placed on internal and external hydrogen explosion hazards; more conventional problems are also summarized and corrective measures noted. Candidate R&D projects are suggested. The contractor is International Energy Associates, Ltd. *EPRI Project Managers: Henry Till and A. D. Miller*

Special RETRAN Modeling Studies Performed in Conjunction With the Peach Bottom-2 Transient Test Analysis

NP-1842 Final Report (RP1119-1); $11.00

Four studies performed in conjunction with the RETRAN analysis of the Peach Bottom-2 BWR turbine trip tests are covered in this report. The studies investigated pressure wave effects in the system; two BWR control systems, the level-feed flow controller and the pressure controller; integral steam separators used in BWRs; and the steady-state relationship between recirculation pump speed and system flow rates. The contractor is Oregon State University. *EPRI Project Manager: J. A. Naser*

RETRAN-02 Program for Transient Thermal-Hydraulic Analysis of Complex Fluid Flow Systems: Equations and Numerics

NP-1850 Final Report, Vol. 1 (RP889); $41.00

The RETRAN-02 computer code was developed from RETRAN-01 and is part of an effort to provide a versatile, reliable thermal-hydraulic code for use in best-estimate analysis of LWR systems. This volume details the theoretical development of the general equations, the constitutive relationships, and the numerical solution techniques of the code. The contractor is Energy Incorporated. *EPRI Project Manager: L. J. Agee*

WAMCOM: Common-Cause Methodologies Using Large Fault Trees

NP-1851 Final Report (RP1233-1); $9.50

This report describes the computer code WAMCOM, which was developed to deal with individual and combined common-cause events and random-failure events. WAMCOM is designed for the experienced analyst working with large, complex fault trees. Descriptive cause sets of susceptible system components are identified, and a sample problem and a user's guide are provided. The contractor is Science Applications, Inc. *EPRI Project Manager: G. S. Lellouche*

A Technique to Reliably Estimate Earthquake Recurrence Intervals

NP-1857 Interim Report (RP1233-1); $9.50

A methodology developed to estimate earthquake recurrence intervals is described. Various earthquake data bases, including that of the National Geophysical and Solar-Terrestrial Data Center, were examined, and statistical analysis results for the available data are presented. The report discusses observations of a regularity in earthquake frequency-magnitude distributions that is applicable to large geographic regions and smaller tectonic zones of both seismically active and nonactive areas. The contractor is Science Applications, Inc. *EPRI Project Manager: G. S. Lellouche*

Visual Inspection Equipment for the Secondary Side of Steam Generators

NP-1859 Final Report (RPS155-1); $8.00

This report describes the development of miniature equipment for the visual inspection of regions inside the tube bundles of nuclear steam generators to determine such factors as gap condition, tube outside surface condition, and material buildup. Tube-support plate interfaces at the tenth support plate level in a once-through steam generator (Oconee-1) were visually examined. Other areas in the peripheral region were examined for conditions associated with available eddy-current and profilometer data. The contractor is Babcock & Wilcox Co. *EPRI Project Manager: G. W. DeYoung*

Demonstration Tests on PWR Steam Generator Tube-Tubesheet Crevice Flushing Procedures

NP-1861 Final Report (RPS183-1); $9.50

A series of autoclave tests was conducted to evaluate the effectiveness of a depressurization flushing technique in removing contaminants from a simulated nuclear steam generator tube-tubesheet crevice. Flushing by depressurization was found to remove substantial portions of sodium hydroxide from open and packed crevices. Additional work is required to optimize the technique. The contractor is Westinghouse Electric Corp. *EPRI Project Manager: D. A. Steininger*

Occupational Radiation-Exposure Reduction Technology Planning Study

NP-1862 Final Report (TPS79-761); $15.50

This report summarizes available LWR occupational radiation-exposure (ORE) data and describes the methods used at commercial nuclear power stations to acquire and manage these data. Four major tasks are described: (1) the assessment of the capabilities of 36 operational ORE data management systems, (2) a survey of ORE studies, (3) the sponsorship of an ORE workshop, and (4) the identification of R&D for the reduction of ORE. The contractor is Stone & Webster Engineering Corp. *EPRI Project Manager: M. D. Naughton*

Secondary Water Chemistry Control at Genkai No. 1: Design and Operating Considerations

NP-1863 Topical Report (RPS170-1); $11.00

This report summarizes the design characteristics, construction materials, operating philosophy, and water chemistry history of Kyushu Electric's Genkai No. 1 nuclear power station. It discusses the secondary system chemistry, sampling and analytic procedures, and chemistry control during wet and dry layups. The appendix describes condensate demineralizer regeneration procedures and design. The contractor is NWT Corp. *EPRI Project Manager: C. S. Welty, Jr.*

RACAP-1 (Reactor Accident Consequence Analysis Program, First Version): Theory and Methods

NP-1871 Interim Report, Vol. 1 (RP1233-1); $18.50

This volume presents the background of nuclear reactor accident consequence analysis and introduces the RACAP concept. The general features and requirements of nuclear reactor risk assessment are outlined, including the role of accident phenomena. The several subtasks connected with the quantification of radioactivity releases are identified, and the relationship between containment integrity and specific emergency safety feature operation or failure is illustrated in event tree form. The contractor is Science Applications, Inc. *EPRI Project Managers: P. G. Bailey and G. S. Lellouche*

Workshop Proceedings: Corrosion of Inconel 600 Steam Generator Tubing in the Tubesheet Crevice

WS-80-157 Workshop Proceedings; $27.50

EPRI and the Steam Generator Owners Group sponsored a workshop in Palo Alto, California, in September 1980 on the cracking and intergranular attack of Inconel 600 tubing in tubesheet crevices in nuclear steam generators. The following areas were examined: plant operating experience, steam generator bulk water and sludge chemical environments, laboratory work on the mechanisms of concentration and corrosion in steam generator tubesheet crevices, transferrable knowledge from other corrosion cracking environments, and corrective measures. *EPRI Project Manager: J. P. N. Paine*

R&D PLANNING AND EVALUATION

Coal-Fired Power Plant Capital Cost Estimates

PE-1865 Final Report (TPS78-810); $15.50

This report presents conceptual designs and order-of-magnitude capital cost estimates (based on mid-1978 dollars) for 15 representative 1000-MW coal-fired power plants. Cost and performance estimates were made for both subcritical and supercritical steam plants, and cost estimates for each plant's fluidized gas desulfurization system were included to reflect June 1979 New Source Performance Standards for SO_2 emissions. Site selection and coal sources, plant descriptions, and results of a comparative analysis of cost data are included. The contractor is Bechtel Power Corp. *EPRI Project Manager: R. A. Loth*

ELECTRIC POWER RESEARCH INSTITUTE
Post Office Box 10412, Palo Alto, California 94303

NONPROFIT ORGANIZATION
U.S. POSTAGE
PAID
PERMIT NUMBER 7577
SAN FRANCISCO, CALIFORNIA

EPRI

ADDRESS CORRECTION REQUESTED

September 1981