Chernobyl in Perspective

ELECTRIC POWER RESEARCH INSTITUTE

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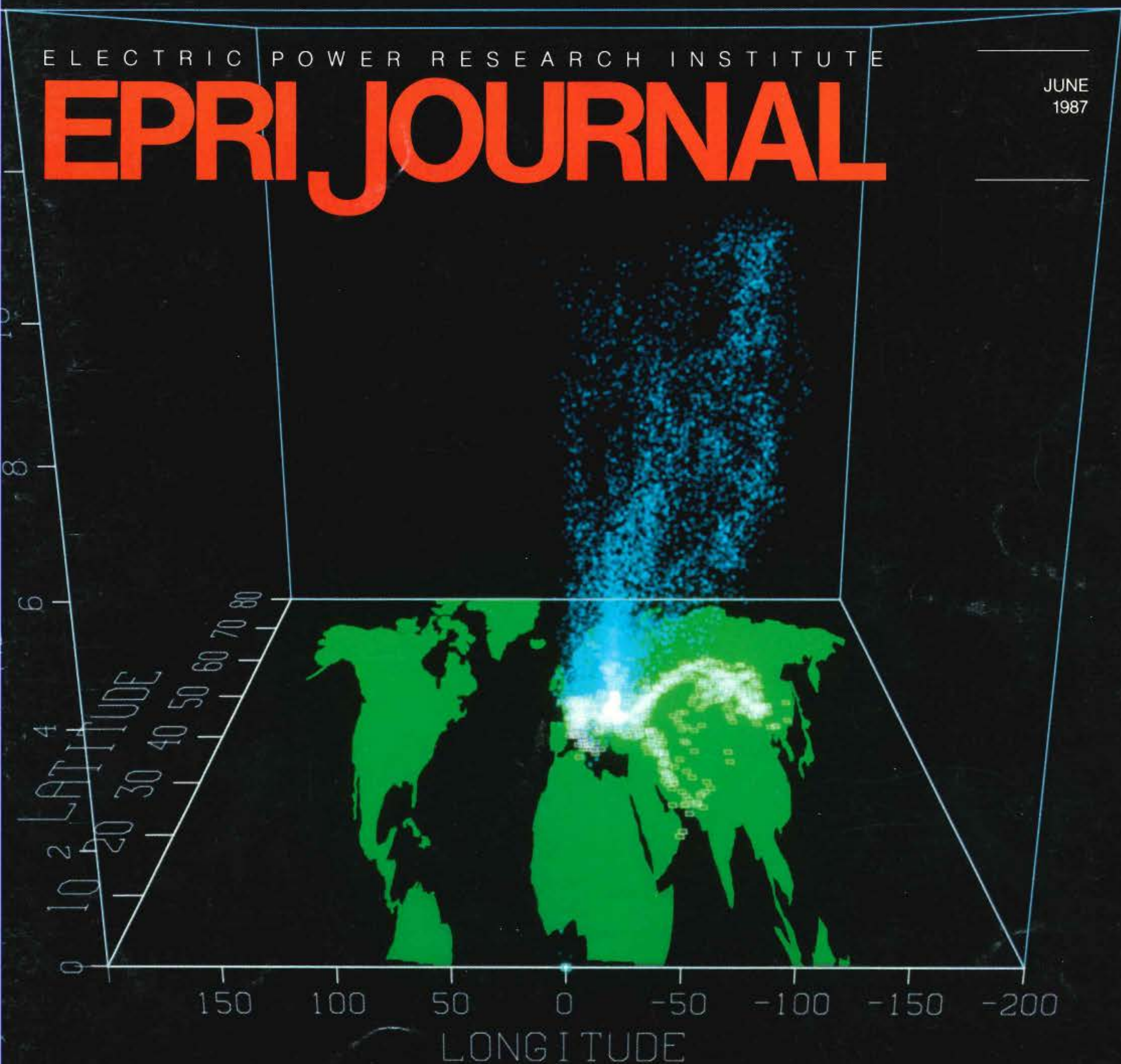

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Cover: This computer-generated graph, based on meteorological and radiological observations coupled with an atmospheric dispersion model, shows the distribution and elevation of radioactive material on May 1, 1986, six days after the beginning of the Chernobyl reactor accident. (Image by Paul Gudiksen, Rolf Lange, and Stanley Grotch, courtesy of Lawrence Livermore National Laboratory)

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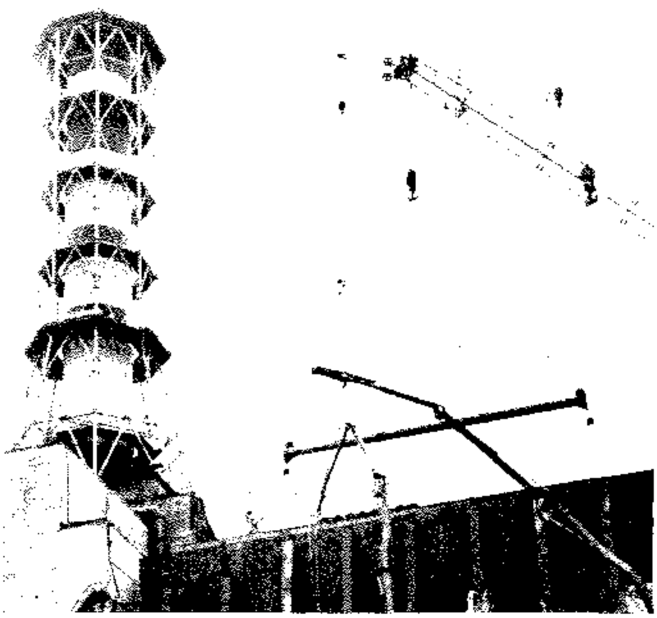

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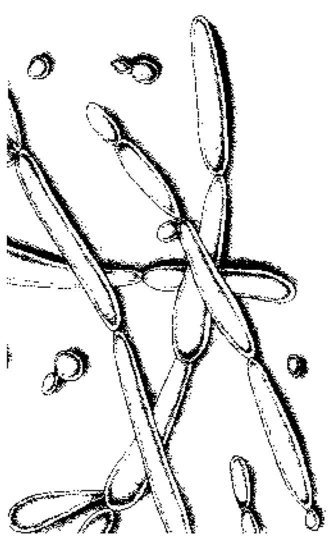


FEATURES

DEPARTMENTS

R&D STATUS REPORTS

Chernobyl: U.S. Impact and Response

Taylor

The U.S. utility industry's response to the Chernobyl tragedy was quick and effective. Under the leadership of Byron Lee, then executive vice president of Commonwealth Edison, the Industry Technical Review Group on Chernobyl investigated the accident closely, sought to identify whatever lessons there might be for U.S. reactors, and gave direction to the industry's response to the legitimate questions raised by the event. EPRI played a key role in supporting the review group in its activities, including the drafting of an Industry Position Paper and an Industry Plan of Response. The perspectives generated through these inquiries are discussed in this month's lead article.

Now, despite a difficult and challenging year, the U.S. nuclear utility industry should be looking beyond Chernobyl with a sense of optimism. There is a strong consensus in the scientific, regulatory, and academic communities that the Soviet accident should not impact the design and regulation of U.S. nuclear reactors. In effect, Chernobyl has validated the value of conservative U.S. designs and our defense-in-depth approach. The Nuclear Regulatory Commission has concluded that no immediate regulatory action is needed and that the accident reinforces requirements already existing or being developed.

In reflecting on Chernobyl, I believe three points need to be reemphasized. First, in an era of renewed interest in international nuclear cooperation, we must keep a proper perspective on where the largest gains in safety can be made. The RBMK-1000 reactor still has serious design weaknesses and remains "unlicensable" by Western standards. It is still unstable, still has a slow scram system, and still cannot handle pipe breaks above the core or multiple breaks inside the core. The Soviets do not intend to put a full containment around their existing RBMKs.

Second, we see nothing in the Chernobyl accident that causes us to reconsider the choices we and our utility advisers are making with regard to future generating capacity. It is imperative that utilities have options for both clean-burning coal and nuclear generation. Nuclear power is not risk-free, but a reasoned analysis of all our energy options points to nuclear power as an essential part of our future.

Third, Chernobyl has provided a vivid case study on the results of complacency in reactor operations. The Institute of Nuclear Power Operations has taken the initiative in communicating that lesson to the management and operating staff of U.S. nuclear plants. Equally important, Chernobyl confirms the wisdom of our industry's decision to establish the Nuclear Management and Resources Council (NUMARC) and of our continued commitment to set ever-increasing standards of excellence. These actions, recommended by the Sillin committee before Chernobyl, would have taken place without the accident. However, the Soviet accident has underscored the timeliness of our commitment and has strengthened it. EPRI stands ready to support NUMARC and its new president, Byron Lee, in reaching its objectives.

John J. Taylor
Vice President, Nuclear Power Division

Authors and Articles

Loewenstein Vine Atherton

Chernobyl and Its Legacy (page 4) distills a year of inquiry into the world's benchmark nuclear power accident, yielding a compact summary of the events and interpretations that are influencing nuclear power programs here and abroad. Written by Taylor Moore, the *Journal*'s senior feature writer, and David Dietrich, its managing editor, with the close help of two research managers in EPRI's Nuclear Power Division and with commentary from many others at the Institute.

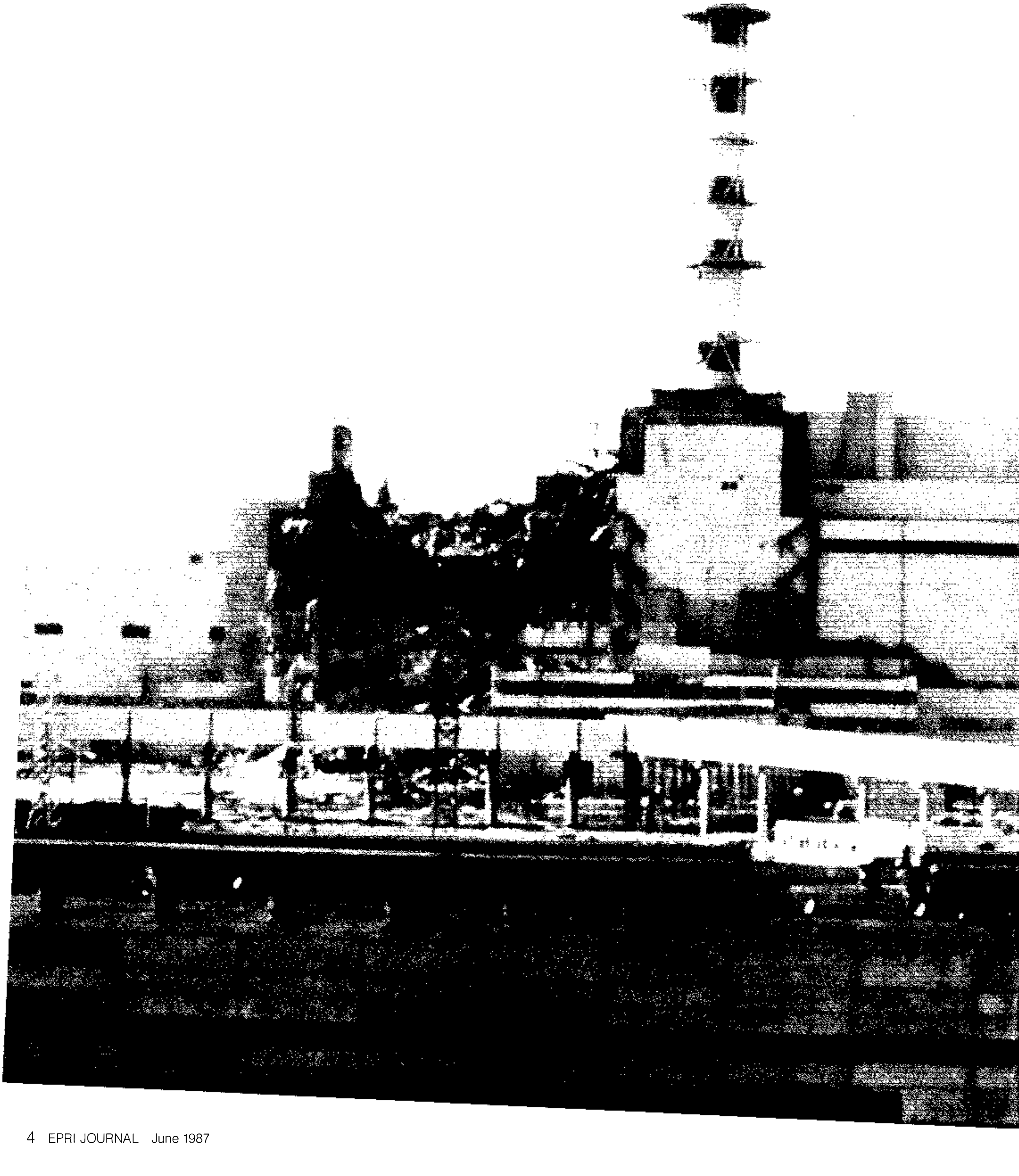
Walter Loewenstein, deputy director of the Nuclear Power Division, has been with EPRI since 1973 and was director of the division's Safety Technology Department for many years. From 1954 to 1973 he was at Argonne National Laboratory, where he became director of its applied physics division. Loewenstein has a BS in physics and mathematics from the University of Puget Sound and a PhD in physics from Ohio State University.

Gary Vine, a project manager in the Nuclear Safety Analysis Center, has been with EPRI since 1981. He was formerly in the Navy for 11 years, serving successively as a nuclear propulsion officer and an operations officer on submarines, then as a fleet specialist for submarine sonar systems. Vine is a physicist, with a BS from the U.S. Naval Academy and an MS from the U.S. Naval Postgraduate School in California. ■

Robert Koger: Study in the Public Interest (page 22) traces the inquisitive career of a state utility commissioner who has served on EPRI's Advisory Council longer than any other person. Written by Ralph Whitaker, *Journal* feature editor, after an interview with Koger. ■

Bugs and Coal: Processing Fuels With Biotechnology (page 28) reports on what seems like 21st-century science being written ahead of time—the use of fungi and other biologic organisms to upgrade, liquefy, and gasify coal. Written by Michael Shepard, *Journal* feature writer, with cooperation from the staff of EPRI's Advanced Power Systems Division.

Linda Atherton, a project manager in the Fuel Science and Conversion Program, has worked in coal gasification and liquefaction since she came to EPRI in 1974. She was previously a senior scientist with the Palo Alto (California) Research Laboratory of Lockheed Missiles & Space Co., Inc., and still earlier a process engineer with Brown & Root, Inc. Atherton graduated in chemical engineering and mathematics from Rice University; she earned MS and Engineer degrees in chemical engineering from Rice and Stanford University, respectively. ■

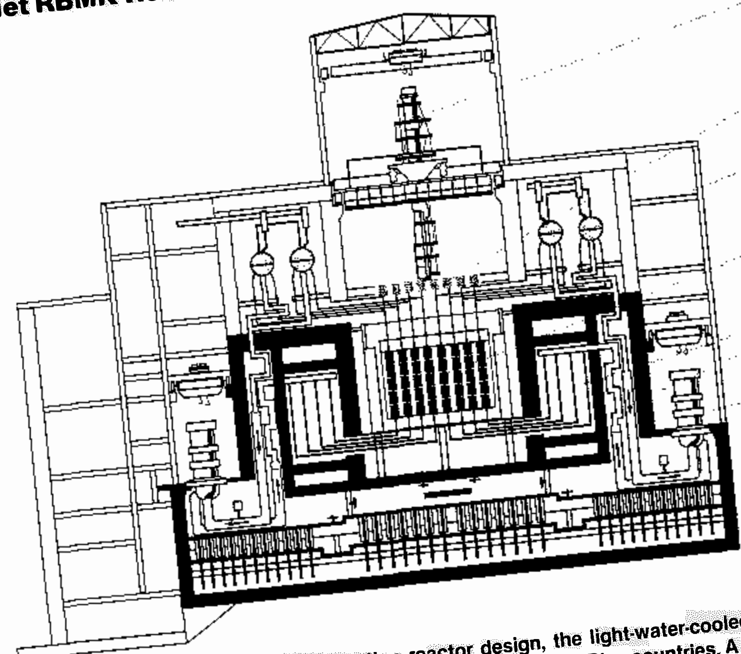


A SPECIAL REPORT

CHERNOBYL

AND ITS LEGACY

The Soviet RBMK Reactor: Unique and Unstable



Descended from a military plutonium-production reactor design, the light-water-cooled, graphite-moderated pressure-tube power reactor series designated RBMK is unique to the Soviet Union and East Bloc countries. A key characteristic of the 1000-MW(e) units, of which there are 15 operating in the USSR, makes them difficult to control and particularly unstable at low power (positive void coefficient of reactivity). The RBMK employs a complex core monitoring and control system, but reactor shutdown (scram) systems are slow and there is inadequate separation of control and protection systems. Moreover, RBMKs lack Western-style containment structures.

What were the underlying causes of the Chernobyl accident, and what are its long-term implications? Could the same thing happen here? A year of investigation and evaluation has provided new insights into the impact of history's most severe nuclear accident.

Novosti/Gamma-Liaison

THE ACCIDENT SCENE

A shift supervisor at Chernobyl Unit 1 measures radiation levels of reactor pressure tubes from the refueling floor more than a month after the accident at nearby Unit 4.
(Photo: Tass/Sovfoto)

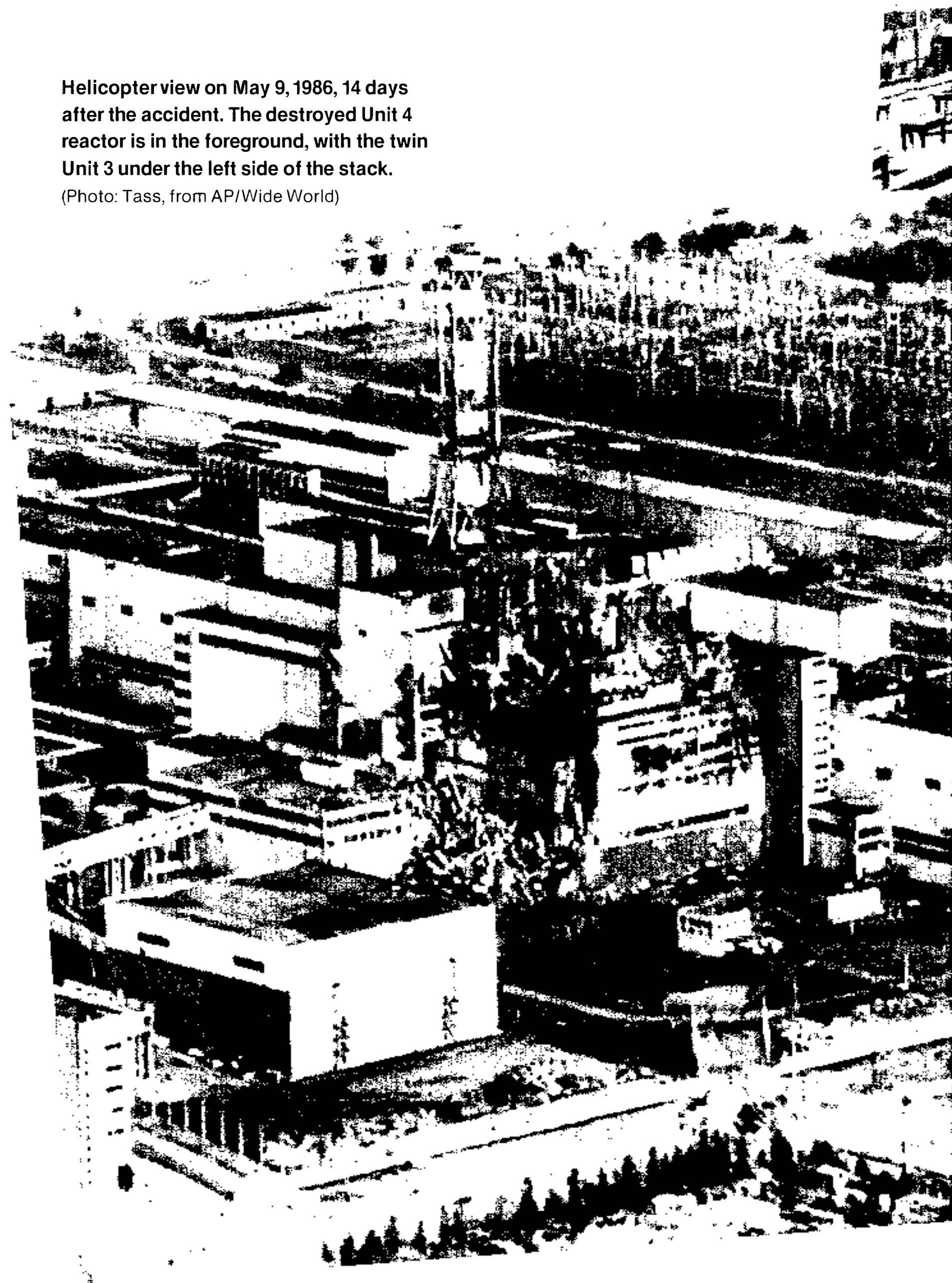
Thirteen months ago an accident at Unit 4 of the Chernobyl Atomic Power Station in the Soviet Ukraine kept the world on the edge of its seat for nearly a fortnight. Repercussions from the accident continue to be felt around the world.

In addition to taking a human toll, Chernobyl revived the debate over the safety and acceptability of nuclear power. The accident has led to delays in the nuclear power programs of several countries (though not the Soviet Union's) while apparently having little real effect in others, experts say. In the United States it once again put the utility and nuclear industries, as well as the government, on the defensive regarding all things nuclear.

Worldwide, the response of the nuclear regulatory and R&D communities to Chernobyl has been staggering. Lord Walter Marshall of Goring, chairman of Britain's Central Electricity Generating Board, says Chernobyl joins the 1979 accident at Three Mile Island (TMI) as an event that will dominate the progress of the nuclear industry worldwide for some time. "A year ago I would have agreed that the nuclear industry was recovering from the setback of Three Mile Island," he told a 30th anniversary gathering of the Japan Atomic Energy Commission last October. "But now . . . for the first time civil nuclear power has caused fatalities. The Chernobyl accident was a colossal event with tremendous implications for the Russians themselves and for the remainder of the world. Clearly the accident is a great setback to the development of nuclear power.

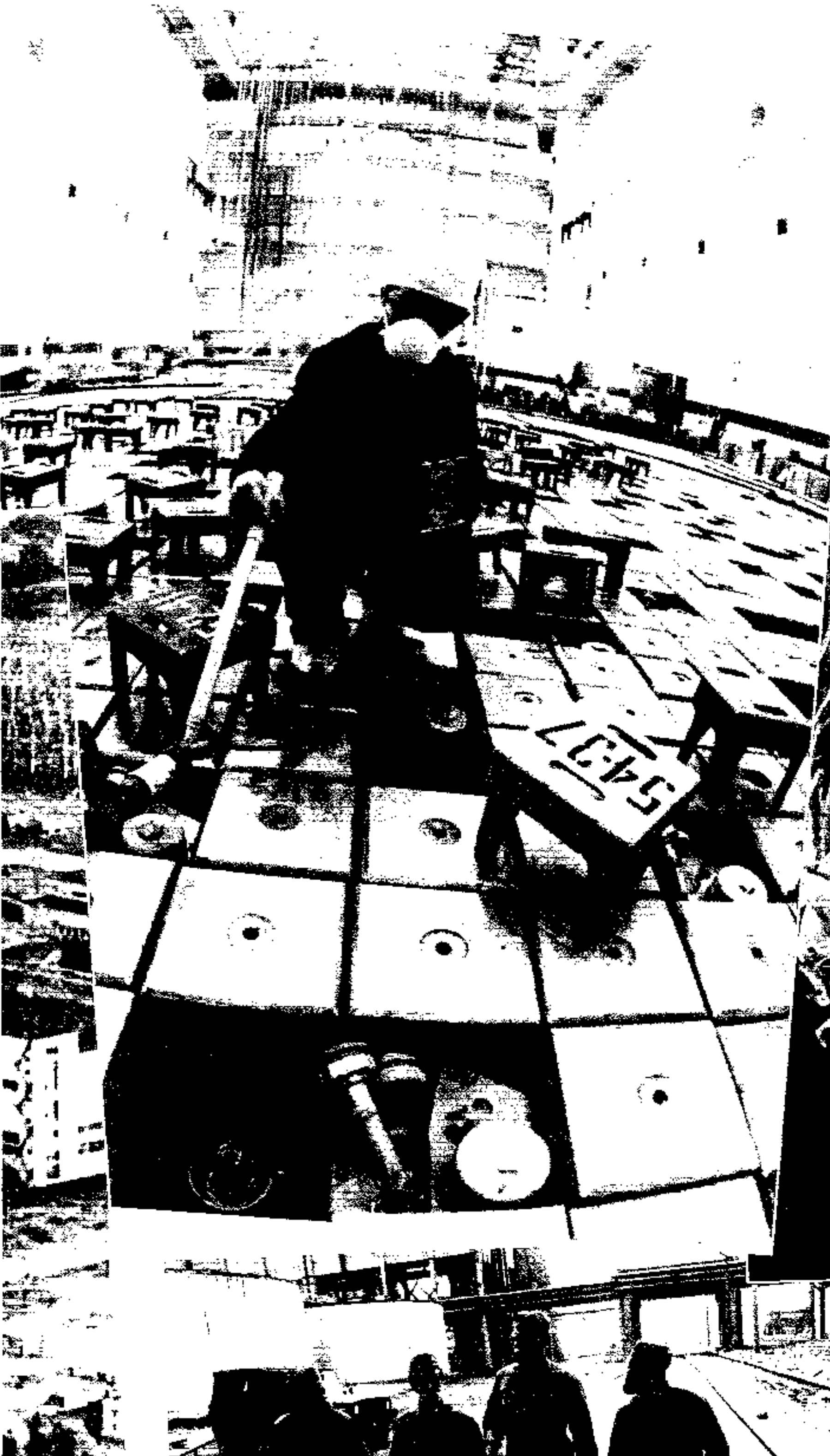
"In some countries," says Marshall, "the shock has been so great that governments have made a formal decision to abandon nuclear power. This is very sad and, in my opinion, their reaction is too quick and too emotional. We all need to take time to see the Chernobyl events in proper perspective."

Several international congresses have



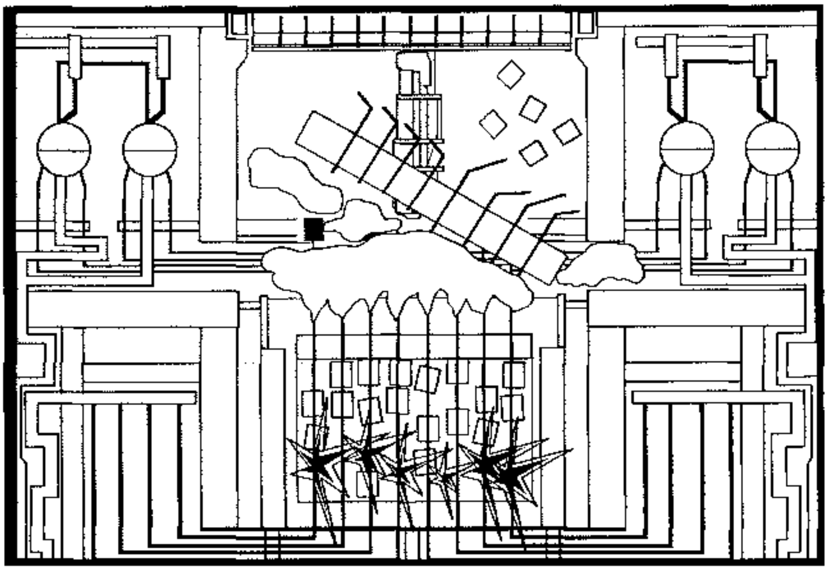
Helicopter view on May 9, 1986, 14 days after the accident. The destroyed Unit 4 reactor is in the foreground, with the twin Unit 3 under the left side of the stack.
(Photo: Tass, from AP/Wide World)

Emergency response crews in a helicopter check radiation levels near the plant.
(Photo: Novosti/Gamma-Liaison)



Plant workers wearing face masks to prevent inhalation of contaminated dust.
(Photo: Novosti/Gamma-Liaison)

The Accident Sequence



Among the many types of reactors in use around the world, the RBMK reactor is unique in several ways that make it particularly vulnerable to power excursions and potential severe accidents, experts say. One of the most important of these is a positive void coefficient of reactivity under most operating conditions. "This means that any increase in reactor power increases coolant boiling, which increases the steam void fraction, which in turn increases core reactivity and causes the power to rise even further," explains NSAC's Gary Vine. In the simplest terms, Soviet RBMK reactors are difficult to control under the best conditions, and their safety design considers only a limited range of accident initiators.

In April 1986 both the design and the human element failed. The accident occurred during a test of the ability—in the event of a turbine trip, reactor trip, and loss of station electric power—of one of the two turbogenerators to power a main feedwater pump for about one minute, long enough to provide emergency core cooling while standby diesel generators power up to full load. The same test had been carried out some months earlier at a similar RBMK unit.

"In setting up the test, the operators put the plant in a very dangerous condition," says John Taylor. "They pulled essentially all the control rods out of the core to the point that they could not shut down the reactor rapidly if needed." The test plan called for the reactor power to be reduced to between 22% and 32% of full power, but because of the operators' failure to synchronize automatic and manual control rods, the power dropped to as low as 1%. This caused the operators to almost fully withdraw all control rods before they were able to stabilize power at a maximum of about 7%. They proceeded with the test at this power level, in violation of the test's power limits, Taylor explains.

In order to prevent the reactor from automatically shutting down, several safety-related systems, including emergency core cooling and some automatic scram circuits, were disconnected, according to the Soviet report on the accident. With the reactor at much lower power than planned and all eight main recirculation pumps at full speed (only six are normally running), coolant flow was significantly above that required for 100% power. This created a nearly solid-water condition in the pressure tubes (almost zero void fraction), with the rest of the cooling circuit near saturation.

With the plant already in an unstable and vulnerable state, the operators tripped the turbogenerator to initiate the test, causing four of the eight recirculation pumps to coast down. This would have initiated a scram if scram circuits had not been disconnected. Coolant flow decreased, causing voids to reform rapidly in the pressure tubes, which increased reactivity because of the positive void coefficient.

Within seconds, the reactor power reached a level prompting the shift manager to order an emergency manual scram, but the almost fully withdrawn control rods could not insert negative reactivity fast enough because of slow rod speeds. In addition, this high rod position permitted an unexpected insertion of positive reactivity in the bottom of the core. As the control rods were reinserted, cooling water was displaced from the control rod channels by undersized graphite rod followers, bringing a surge in neutron flux in the bottom of the core. The reactor went on a prompt critical (runaway) power excursion. Seconds later, two distinct shocks were felt 2–3 seconds apart, as power went off-scale (almost 500 times nominal, by Soviet computer reconstruction). Fuel overheated very rapidly and shattered, causing the coolant to flash to steam in the fuel channels, which then ruptured from excessive temperature and pressure. The steam pressure blew the 1000-ton steel- and cement-filled biologic shield off the top of the reactor, severing all pressure tubes and connecting pipes and exposing the core to the atmosphere. □

analyzed the accident for lessons that might apply to other reactors, as well as for insights on emergency planning and response. The United Nations' International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency of the Organization for Economic Cooperation and Development have been particularly active in this effort. Utilities from many countries, including the United States, have joined these organizations in a movement toward a new international regime of nuclear safety and cooperation.

At EPRI, home to the U.S. utility industry's Nuclear Safety Analysis Center (NSAC), Chernobyl's impact has been substantial. EPRI specialists have testified before congressional committees, the Nuclear Regulatory Commission (NRC), and other panels; have participated in all the international postaccident review meetings and definitive studies; and have been at the heart of the utility industry's technical assessment of the accident and its implications for American nuclear power.

According to EPRI Vice President and Nuclear Power Division Director John Taylor, "EPRI has a responsibility to the utilities to make an in-depth technical evaluation of the accident and its consequences." That assessment is reflected in the official U.S. nuclear industry position paper on Chernobyl, prepared by a special technical review group appointed by the Utility Nuclear Power Oversight Committee and chaired by Byron Lee, executive vice president of Commonwealth Edison Co. Taylor was a member of this review panel.

Why did the accident happen?

Beyond detailing the actual sequence of events precipitating the accident, the industry paper draws a number of conclusions on the underlying causes of the Chernobyl disaster, attributing blame to both the reactor design and operator error. The prevailing conclusion, confirmed by NRC, is that there are no immediate lessons to be learned by the West in terms of reactor design. As Taylor told Senate and House subcommittees last June, "Soviet designs are so different from U. S. light water reactors that it is difficult to draw easy applications to our situation. Many of the lessons of Chernobyl will simply not apply to U.S. plants."

Gary Vine, of NSAC, who tracked and studied the Chernobyl accident for EPRI and authored the safety analysis chapter of the U.S. interagency factual report (NUREG-1250), elaborates: "The RBMK reactor is unique in several ways that make it particularly vulnerable to power excursions and potential severe accidents. Among the most important of these is a positive void coefficient of reactivity under most operating conditions, which makes RBMKs difficult to control, especially at low power. The resulting extreme sensitivity to reactivity perturbations requires a complex core monitoring and control system to maintain stability."

Other inherent problems in the RBMK are a relatively slow emergency shutdown (scram) system and a very limited pressure-suppression capability.

In contrast to the U.S.-designed light water reactor (LWR), which has a 6- to 8-inch-thick steel pressure vessel that surrounds the core, the primary pressure boundary in the RBMK design consists of the over 1600 individual zirconium pressure tubes, each about 4 millimeters thick, that contain the fuel rods. The reactor vault shell surrounding these tubes can withstand a rupture in only one tube before the shell fails. According to Vine, many of these pressure tubes ruptured simultaneously inside the core vault during the accident, an event not considered in the Soviets' design basis.

The steel and concrete containment dome that completely encloses the entire reactor coolant pressure boundary in a Western LWR is missing from the RBMK; the Soviet "accident localization system" surrounds only piping that enters the reactor, leaving 20–30 miles of coolant exit piping and four large steam separators uncontained. The fact that the reactor's massive graphite core moderator can burn in the presence of oxygen increases the potential seriousness of an accident.

The deficiencies of the RBMK design reflect not so much a disregard for safety as a more constrained historical development path (see box, p. 16) and differences in safety philosophy. The Soviets appear to rely more heavily on operator actions to prevent accidents than on inherently safe designs, defense in depth, and human factors engineering—the hallmarks of LWR safety. Indeed, in their assessment of the Chernobyl accident before the world nuclear community last August in Vienna, the Soviets downplayed the design weaknesses of the RBMK reactor and focused instead on operator errors and departures from procedure, of which there were several.

IRONICALLY, the accident occurred during a test of the plant's ability to provide emergency core cooling during a loss of the station's electric power. In this case not only were the test procedures not followed closely but the test itself was apparently improperly designed and supervised. Moreover, it is thought that the operators were under pressure to conduct the test just before a scheduled maintenance shutdown and the start of the national May Day holiday.

"In setting up the test, the operators put the plant in a very dangerous condition," notes John Taylor. "They pulled essentially all the control rods out of the core to the point that they could not shut down the reactor rapidly if needed." In addition, several safety systems, including many automatic scram circuits and the emergency core cooling system, were intentionally disconnected to allow the test to proceed. After the accident the Soviets identified six distinct and serious violations of procedures by the operators.

What went wrong in terms of human factors at Chernobyl? INSAG, the safety advisory group of IAEA, argues that the accident shows a need for greater automation to improve the man-machine interface. NSAC's Gary Vine has mixed feelings about this conclusion: "The INSAG report on Chernobyl takes the position that the interface between the man and the machine—typically composed of information display systems, computer diagnostics, and so forth—is very important to overall safety, and that Chernobyl indicates a need for improvement. We would agree with that statement as a generic conclusion from reactor operating experience, in particular the TMI accident. But from our analysis of the Chernobyl accident, we conclude there were serious problems with the man, serious problems with the machine, but very few obvious problems with the interface between them.

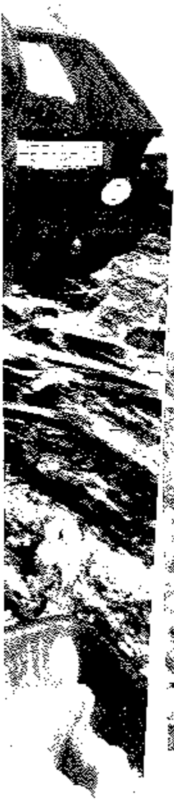
"The Soviets emphasized in Vienna that the operators were very aware of the reactor's unsafe condition and the requirement to shut it down instead of proceeding with the test. More diagnostic aids to tell them that probably would not have helped. The operators did not lack good information, they lacked good judgment. We agree on the generic importance of the man-machine interface, but we don't agree Chernobyl teaches us that lesson," says Vine.

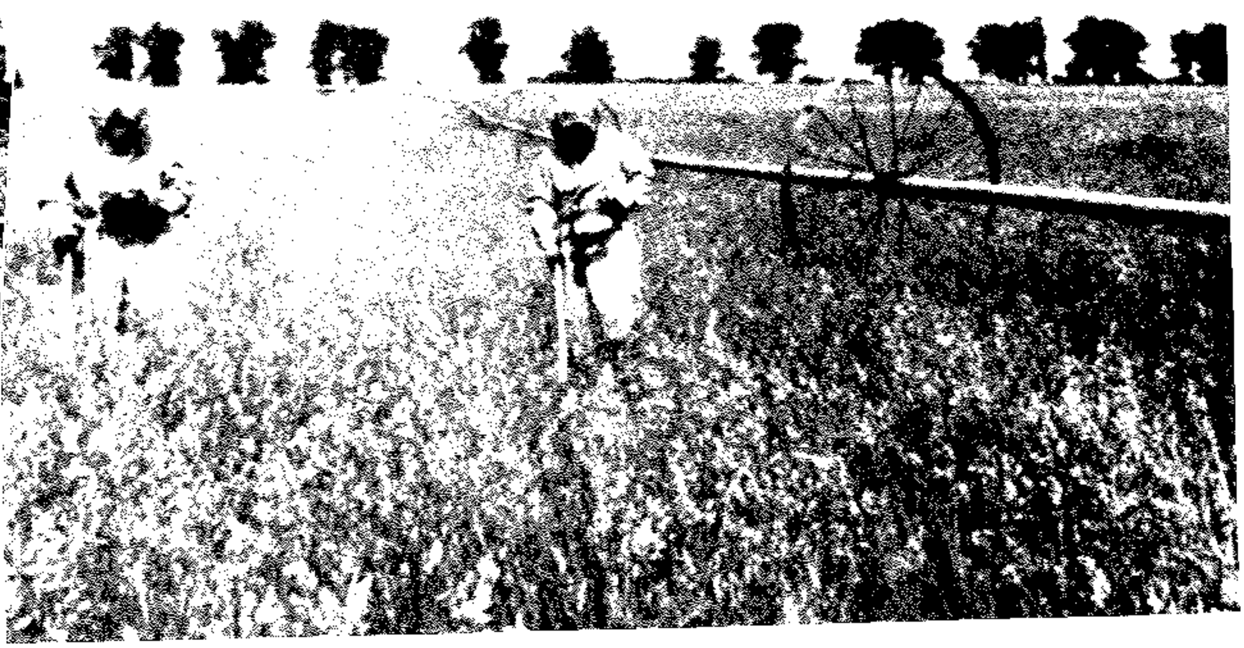
The Soviets have announced their intent to install a number of hardware and procedural changes for RBMK reactors, including new rules on minimum control rod insertion, more in-depth

Solution spraying in the contaminated zone.
(Photo: Novosti/Gamma-Liaison)

An automobile leaving Poland is decontaminated after radiation was detected on it at a West German border checkpoint eight days after the reactor accident in the Soviet Union.
(Photo: AP/Wide World)

Radiation checkpoint in the contaminated zone in the Ukraine. (Photo: Novosti/Gamma-Liaison)





Checking for radiation in the Ukraine. (Photo: Novosti/Gamma-Liaison) safety reviews of tests, higher fuel enrichment to reduce the positive void coefficient, and the addition of faster-acting shutdown systems. These changes deal primarily with preventing the initiation of future Chernobyl-type incidents, but they do not correct the fundamental design problems of the RBMK. "In particular," says Gary Vine, "RBMKs still lack full containment and will still be unable to survive more than one pressure tube rupture."

Soviet response at Chernobyl

Despite some initial confusion on the part of plant management in assessing the Chernobyl accident's severity and in communicating with Moscow, the Soviets are generally credited with responding very effectively to the accident, both at the plant and in evacuating the surrounding population. Soviet officials said later that much was done ad hoc, although extensive general emergency preparations were in place through civil defense programs.

Soon after dawn the morning after the accident, potassium iodide pills to block the uptake of radioiodine by the thyroid gland were distributed to the 45,000 inhabitants of nearby Pripyat, including plant workers; somewhat later, they were distributed to the 70,000–90,000 peasants in 71 villages within 30 kilometers (18 miles) of the plant. The Soviets reported no immediate toxic reactions to the pills, which they credited with limiting thyroid exposures to levels below what would otherwise have been expected.

Because initial radiation readings were low around the plant (the thermal plume above the reactor carried much of the material straight up) but high near key evacuation routes, residents of Pripyat were told to remain indoors and were not evacuated until 36 hours after the accident. Once under way, however, the Pripyat evacuation was accomplished within 3 hours by means of hundreds of buses brought from Kiev, 80 kilometers away. Evacuation of the additional people within 30 kilometers started later and was not completed until about a week after the accident.

Nearly all the evacuees from Pripyat and outlying areas received significant radiation doses, averaging from 3 to 45 rem for various groups. Such doses range far above the normal occupational radiation exposure limit of 5 rem per year, but are below the amount necessary to cause immediate visible health effects. Several hundred plant workers and fire fighters were medically screened and treated for thermal and radiation burns; whole-body gamma-dose measurements were also made.

Ultimately, about 200 plant workers were treated for acute radiation sickness. With the exception of 2 people killed by trauma or the collapse of the reactor building, the 31 deaths were the result of combined thermal burns and radiation exposure. All of the fatalities were plant workers or fire fighters.

DECONTAMINATION around the plant and within the 30-kilometer zone has been an enormous operation, involving thousands of Soviet workers and soldiers, and will continue for some time. The intensity of much of this activity is evidenced by Soviet television scenes of face-masked workers involved in the cleanup near the plant. The Soviets have said that as early as January of this year, 95% of the contamination in Pripyat had been cleaned up, while about 10 square kilometers (4 square miles) and some other areas near the plant remained to be de-

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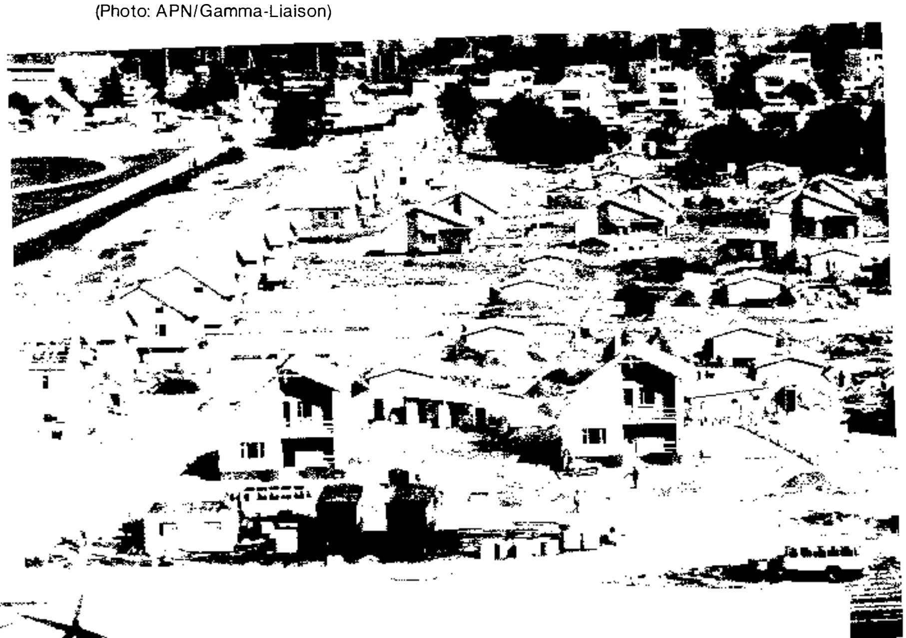
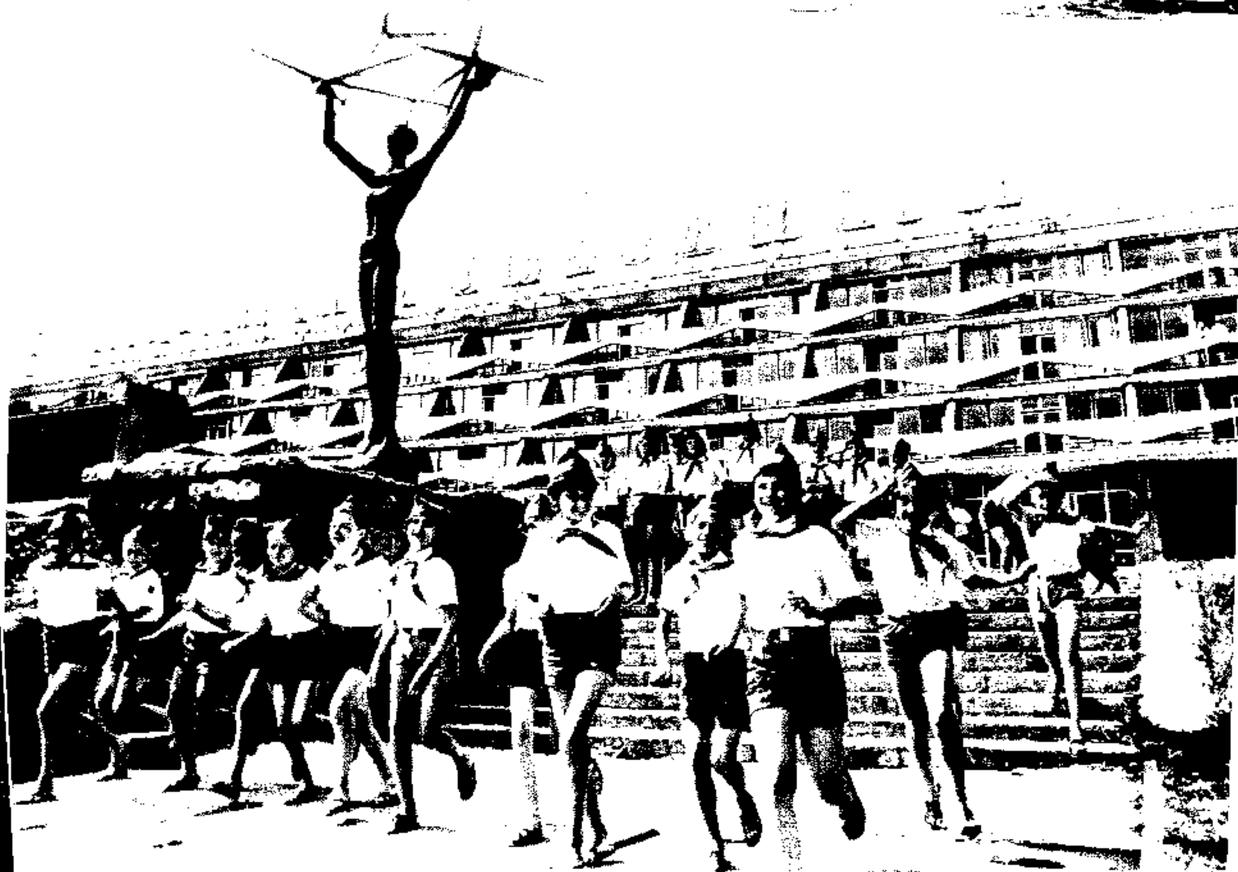
Initially, the Soviets reported that about 135,000 persons were evacuated from within 30 kilometers (18 miles) of the Chernobyl plant site; the total was recently revised to about 116,000. Soon after the accident, children in the contaminated areas of the Ukraine and Belorussia were sent to youth camps in nearby areas. Residents of many villages were temporarily relocated with families outside the contaminated zone. Numerous new villages have been constructed for displaced residents in and near the evacuation zone as areas have been decontaminated.

An air force major-general assisting in the evacuation visits a family at the Ternopolsky resettlement village in the Ukraine, September 198
(Photo: APN/Gamma Liaison)

Displaced Chernobyl-area youngsters are counseled in the Crimea.
(Photo: Novosti/Gamma-Liaison)

Kirov resettlement village under construction in Belorussia, September 1986.
(Photo: APN/Gamma-Liaison)





Evacuated children from Pripyat spending the summer at the Zvezdny Young Pioneer camp near Odessa, Ukraine, September 1986.
(Photo: APN/Gamma-Liaison)

contaminated. Evacuees are now being permitted to return to as near as 10 kilometers (6 miles) from the plant. It is not known when or if areas closer in will be reopened.

Early after the accident, when urgent measures were being taken to cool the damaged reactor and prevent groundwater contamination, the Soviets employed a number of robots for earth moving and the like, although most of the remotely controlled machines were said not to have performed well in high radiation fields. Liquid nitrogen was pumped into the core region to aid in cooling and help extinguish the graphite fire. This action, in combination with the dumping of several thousand tons of various materials (sand, lead, clay, and boron) on the core from helicopters, did eventually put out the fire, halting large releases by day 10. Dikes and trenches were made to limit contamination of the nearby Pripyat River and the Kiev Reservoir to the south; and in many areas, soil layers of several centimeters were scraped off for disposal as radioactive waste. Polymeric films have been applied over several hundred thousand square yards to trap contamination and limit its redistribution.

In many surrounding regions, considerable quantities of local foodstuffs (meat, milk products, greens, berries, vegetables, fish) were found to have been contaminated above levels deemed safe and were destroyed. Inconsistencies in the treatment of contaminated foodstuffs by other European countries, however, created much controversy, highlighting a need to improve guidelines for the management of contaminated food.

Chernobyl Units 1 and 2 were restarted late last year; the more seriously contaminated Unit 3, adjacent to the ill-fated reactor, is scheduled for restart this year. The Soviets recently announced that Chernobyl Units 5 and 6, under construction at the time of the accident, will not be completed.

Lessons learned

There are lessons to be learned from the Chernobyl accident, but according to EPRI President Floyd Culler, there are few on the technical side. "U.S. light water reactors are designed to be inherently more stable in reactivity control during transients," says Culler. "They are protected by much faster shutdown systems, which operate independently, and are designed to resist a much wider range of credible accident sequences. And unlike the RBMK reactor," he emphasizes, "they are surrounded by a sealed, strong containment vessel."

As John Taylor told NRC in the early weeks after the accident, TMI—not Chernobyl—was the accident with broad technical lessons for American nuclear power. "In searching through the information on Chernobyl for opportunities for further improvement, we have found that most of the lessons have been learned already and applied in the United States," he said. This is true in large measure because the design aspects that were most responsible for the initiation and severity of the Chernobyl accident simply do not exist in U.S. nuclear plants.

But perhaps more relevant than the specifics is the general approach behind the design. As Don Rubio, director of EPRI's Nuclear Safety Technology Department, points out, Chernobyl confirmed the basic Western philosophy of containment and of defense in depth: "Chernobyl reemphasized the need for the designer to design for failure. Although the accident didn't reveal any new things, it emphasized that if anything can go wrong, it will. We've followed that philosophy in U.S. designs from the beginning, building containments and redundant safety systems, and we've strengthened that approach since TMI."

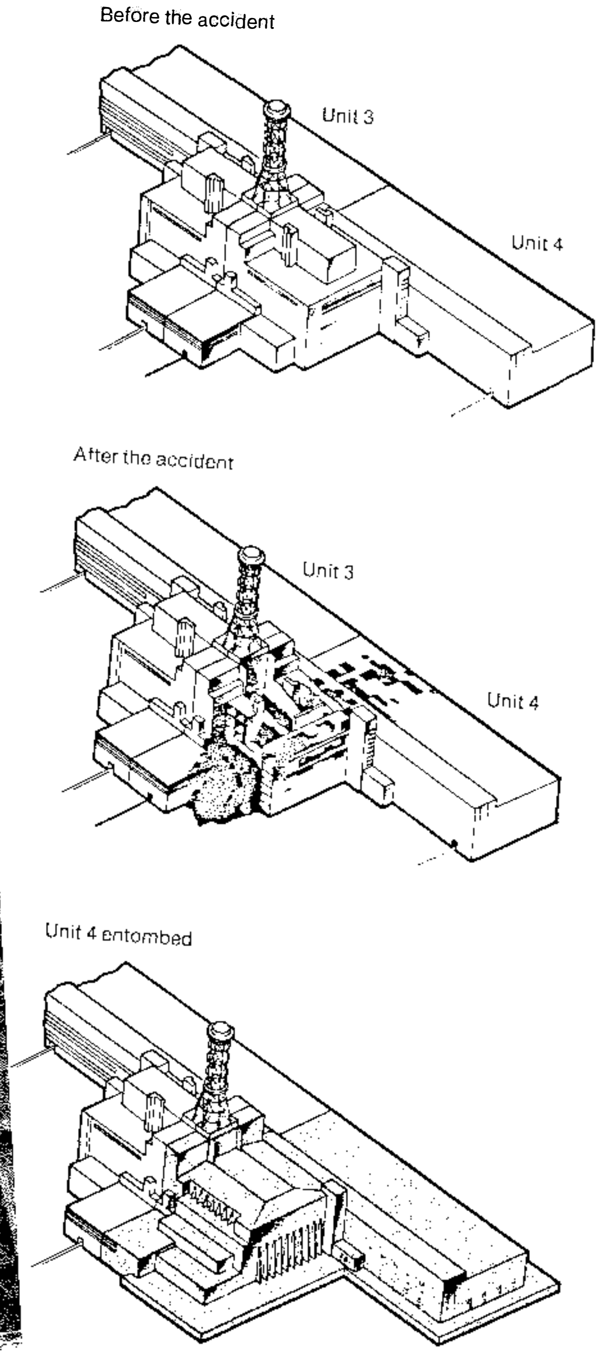
The lessons on human factors are likewise largely confirmatory. "The number of operating violations that preceded the accident leads us to conclude that management controls and operator training and discipline in the Soviet Union are not up to U.S. standards," says Culler. "This should in no way daunt the U.S. nuclear industry in its continuing quest for operational excellence," he adds, "but it suggests we have little to learn from the Soviets in this regard." Some specific areas are being reviewed by the utility industry's Institute of Nuclear Power Operations, including reactivity control procedures and plant testing guidelines.

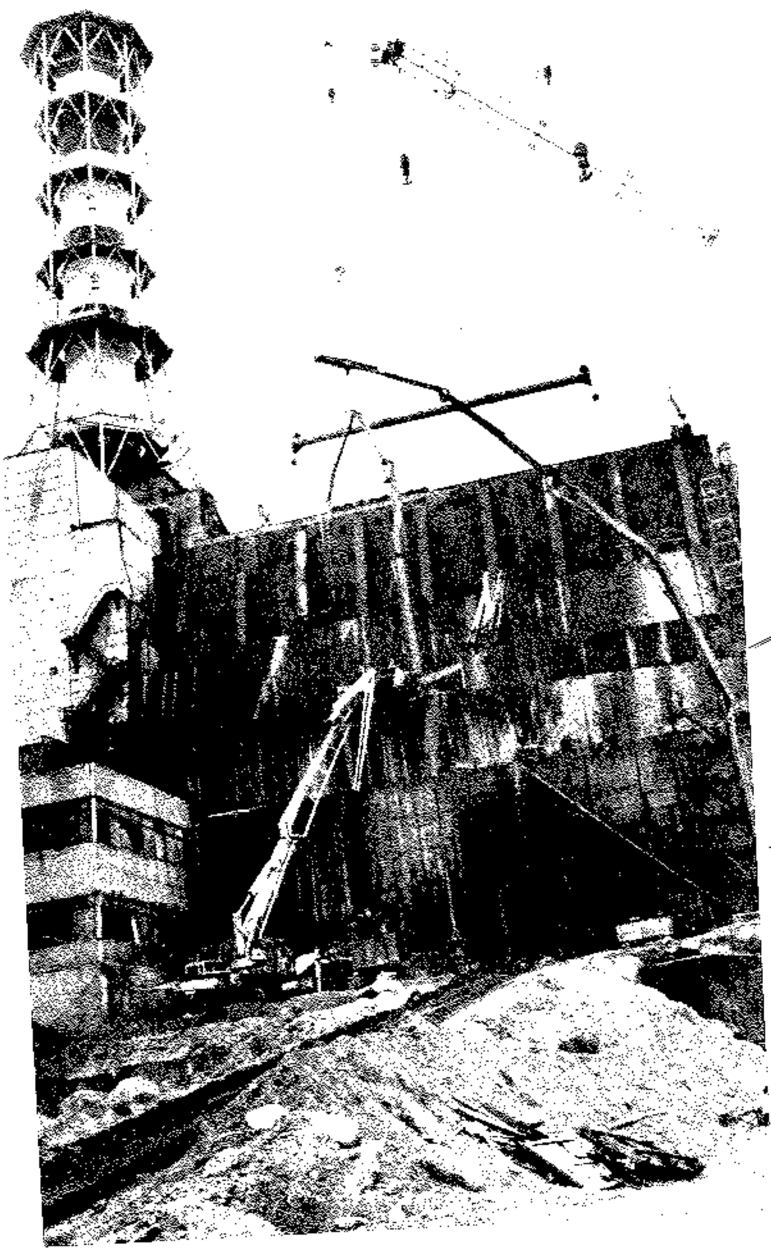
Rubio carries the thought further. "Deep down, 100% of failures are caused by people, either in design, operation, maintenance, or materials application. That says we must design for accidents, train for them, and understand as well as we possibly can how to limit their occurrence and mitigate their consequences."

MOST OF THE NEW KNOWLEDGE emerging from the Chernobyl experience is on the institutional and procedural side. "In this arena," says Floyd Culler, "some of the key information will come from the Soviets' assessment of their emergency planning and response, including questions about evacuation, the effectiveness of potassium iodide pills and the possible reactions to them, emergency health treatment, fire protection and fire fighting in radiation fields, and the levels of land and groundwater contamination."

Some of these lessons were far from appreciated in the early hours of the accident. Dr. Robert Gale, the hematologist and bone marrow transplant

After radiation levels at the crippled reactor had diminished in late 1986, the Soviets constructed a permanent concrete and steel sarcophagus over the destroyed unit to ensure confinement of residual radioactivity. Partition walls in the adjoining turbine hall were erected to isolate the Unit 4 turbine generators from the largely undamaged Unit 3 area. The entombment of Unit 4 permitted the return of plant workers and the resumption of operations at nearby Units 1 and 2 late last year. Unit 3 is being decontaminated and is scheduled for restart this year.





Construction of the entombment, October 1986. (Photo: Tass/Sovfoto) specialist from the University of California at Los Angeles who flew to the Soviet Union to assist in the medical response, provided an example at an EPRI briefing last February. "The delay in evacuating the Pripyat area turned out to be quite appropriate. It proved to be much wiser to keep people in their homes for those initial 36 hours than to evacuate them immediately, which might have moved people into areas of higher exposure. This is an important lesson for any reactor accident," Gale said. "The idea that you should just get people out instantaneously is probably incorrect; someone with first-hand knowledge of the atmospheric conditions, the type and distribution of radiation, and so on needs to make an on-the-spot decision, and it may not always be evacuation."

A variety of therapeutic treatments (transfusions, chemotherapy, antibiotics) were given to the victims, and many led to recovery. However, bone marrow transplantation, one of the more extreme medical interventions, was tried in 13 cases and only 2 survived. The severity of thermal and beta-radiation burns among those who did not survive the transplants was indicated as a major factor in the lower-than-expected success rate.

The long-term effects of radiation are probably the most uncertain of the potential lessons from the Soviet accident. Despite initial concern over the fact that the contamination was centered in the rich cropland of the Ukraine, reports indicate that the long-term damage to Soviet agriculture may be more limited than earlier believed. However, the real effectiveness of the Chernobyl cleanup procedures will take years to verify, as will the long-term human health effects (see box, p. 18). Says Chauncey Starr, EPRI's founder, "Chernobyl is a living experiment—the results of which are not going to be available for 20 or 30 years—on whether the radiation to which people were exposed will pro-

History of the RBMK

Considering the operation and safety shortcomings that have come to light with the Chernobyl accident, why would the Soviets have preferred such a flawed design in the first place? The graphite-pile design from which the RBMK is directly descended was originally chosen by the Soviets in the early 1950s because of its dual capability for producing power and weapons-grade plutonium.

According to Edwin Zebroski, a senior technical adviser in EPRI's Energy Study Center who has toured Soviet nuclear facilities, one probable reason the Soviets decided to continue to pursue the RBMK design was a desire for rapid development despite their lack (at the time) of a manufacturing capability for large pressure vessels. "It is plausible they would have liked to go with pressurized water reactors [PWRs] even in those early days, but didn't have the industrial capability to implement that direction; they may have stuck with the graphite-moderated, tube-type military design solely because it didn't require much heavy fabrication."

By the mid to late seventies, the Soviets did develop PWRs similar in concept to those in the West, including some with concrete containments; but they also continued to build RBMKs, which had definite safety drawbacks. "The Soviets decided many years ago to forgo containments for RBMK reactors because they were seen as impractical and too expensive," explains Zebroski. "To enclose a massive Chernobyl-type reactor, with its 1870-ton graphite core and a 350-ton on-line refueling machine on top, would require a containment building twice as big as the largest Western containment—an expensive and difficult engineering challenge."

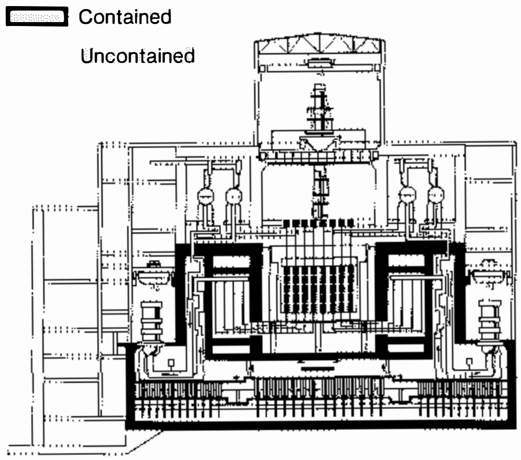
The decision to build both types of reactor led to the evolution of two almost separate design cultures within the Soviet Union, with safety approaches clearly constituting one primary difference between them. "One side carried on the tube-type design on the assumption that, with correct operation of the reactor, a serious accident was impossible and you therefore didn't need a containment," observes Zebroski. "The other side's view—essentially that of the Western nuclear community—said that even if an accident is extremely unlikely, a containment is still necessary to make sure not much radioactive material gets out if the unthinkable happens."

Today half of the Soviet reactors are RBMKs, although plans before the accident called for 44 of the 57 new Soviet reactors scheduled to begin operation by 1995 to be PWRs. Adds Zebroski: "Some of those responsible for RBMK design have been removed from office, and those who remain say they are going to finish most of the ones under construction and not build any more." □

Comparing Reactor Containment

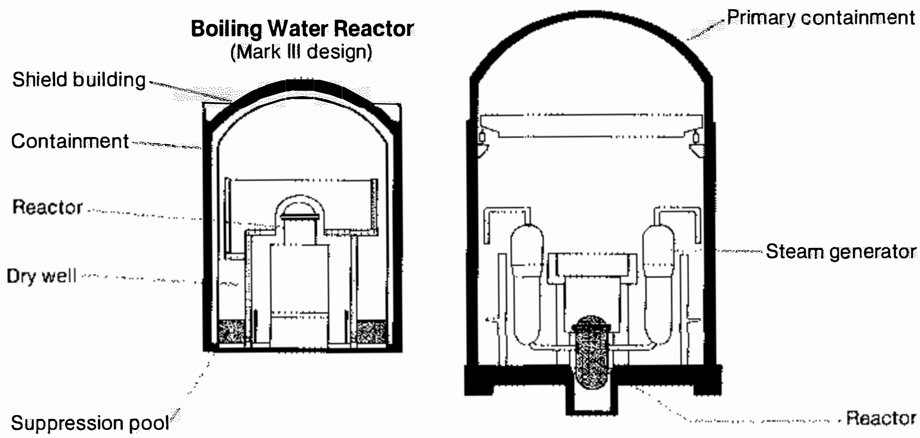
Soviet RBMK reactors do not have containment structures completely enclosing the coolant pressure boundary, as do all U.S. and most Western commercial light water reactors. Limited pressure-suppression capability for single tube breaks and certain large pipe breaks is provided in the most recent RBMKs (including the destroyed Chernobyl Unit 4) by concrete-walled compartments and bubbler pools around and underneath the lower half of the reactor. But the top half of any RBMK unit is essentially uncontained, covered by a heavy biologic shield structure designed to withstand the failure of only one of the 1661 pressure tubes. This means that more than one pressure tube rupture inside the core will destroy the reactor. The reactor and surrounding components and compartments are housed in an ordinary industrial building.

RBMK Reactor



Light water reactors in the United States and elsewhere employ several types of containment structures, depending on whether they are of the pressurized water (PWR) or the boiling water (BWR) variety, but they all have thick, steel-lined concrete domes completely enclosing the reactor system and all pipes entering and leaving the reactor. Most PWRs feature large, dry containments, although some also provide for pressure suppression by means of ice condensers inside the containment. BWRs typically include pressure-suppression water pools inside a containment building.

TYPICAL U.S. REACTOR CONTAINMENTS



Estimating Long-Term Health Effects

Chernobyl cleanup worker with (possibly military) medical personnel at a field clinic.

Novosti/Gamma-Liaison

Perhaps the most uncertain legacy of the Chernobyl accident involves the health effects—mainly leukemias and other cancers—that may result among exposed populations over the next 50–70 years.

Predicting the magnitude of such effects is difficult. One reason is that results cannot be projected directly because we have few actual measurements of the radiation doses received by exposed populations. To develop approximations of received doses, data on the reported radionuclide releases are fed into atmospheric models that simulate the dispersion of the material. Gaps and irregularities in the radioactive deposition data, complicated by natural variations in weather patterns in the days and weeks following the accident, make for significant uncertainties in the results of the atmospheric transport models.

Currently the estimates for collective doses received outside the Soviet Union vary by a factor of 2 to 3 among the various groups of scientists that have made this calculation. For doses inside the Soviet Union, Western scientists generally defer to Soviet estimates, which also involve uncertainty. "Measured [doses] of radioactive cesium from the Chernobyl nuclear accident fallout are 10 to 20 times lower, and external radiation 1.5 to 2 times lower, than the conservative and worst-case assessments made last August in Vienna by Soviet scientists," according to Soviet academician Leonid Ilyin.

After the best estimates of exposure are developed, they are used in dose-response models, which estimate the risk of health effects likely to result from these exposures. The models must consider effects from all radionuclides released, of which iodine-131 and cesium-137 are the most important. The correlation between dose and health effects is statistically distinguishable at high doses—on the order of 10 rem—but must be extrapolated for doses below the range of actual evidence. Therefore, the results are highly dependent on the assumptions and extrapolation theory used.

As EPRI's Leonard Sagan points out, "We have almost no valid observations on radiation risks at low doses, such as those projected for individuals outside the Soviet Union. Hence the various estimates are based on mathematical models, which are in turn based on unvalidated assumptions. One of these assumptions, used largely because of a desire to include a worst, or most conservative, outcome, is that radiation at very low doses will produce effects in the same proportion as at high doses. The evidence for this assumption is fragile—many feel that, as with most agents that are toxic at high doses, there is a dose threshold below which no effects at all occur. Uncertainty in this area is a primary reason for differences in estimates of health effects resulting from the Chernobyl accident."

Cancer is the dominant long-term health effect of concern from additional exposure to ionizing radiation. These effects are commonly expressed in terms of projected excess cancer mortality above the naturally occurring rate, which varies from 13% to 20% for specific global regions. On the basis of revised release estimates and recent extensive whole-body measurements, the Soviets now estimate the probable total excess cancers in the evacuation zone at 160, which is about 1% of the cancer deaths expected from natural or unknown causes, independent of the accident. Outside the evacuation zone, the Soviets predict a total of 0.03% to 0.08% additional cancers among the 75 million people in the European USSR, which would work out to an increase of about 3000 to 8000 additional cases. Over a million measurements have been taken by the Soviets through a comprehensive medical assessment program, and no variation in the health of Chernobyl evacuees due to radiation has yet been discovered.

For Europe (non-USSR), the health effects become much more difficult to predict because the very low doses experienced outside the Soviet Union are well below the range for which actual data on health effects exist. Models predict that the total collective dose to an individual European over the 50 years following the accident will range from a fraction of his annual dose from naturally occurring radiation to as high as three to five years' worth of the annual background dose. The Soviets predict that, on average, some 300 million people in Europe will receive a collective dose "not more than 1.3%" above normal background levels during the 50 years following the accident. International experts of the UN Committee on the Scientific Effects of Atomic Radiation have come to similar conclusions.

A number of scientific organizations in Europe and the United States have modeled the radiation health effects. The principal U.S. reports presenting such model predictions are near publication: an interlaboratory report sponsored by the Department of Energy, and the Nuclear Regulatory Commission's NUREG-1250, with a health effects chapter prepared by the Environmental Protection Agency. The predictions of potential cancer fatalities in Western Europe range from an incremental increase of 0 to 0.03%. The UK's National Radiological Protection Board predicts that the countries of the European Community (a group that does not include Scandinavian or Eastern European countries) can expect 1000 extra deaths (a 0.002% increase) over the next 50 years from cancers caused by Chernobyl. NUREG-1250 predicts a 0.006% increase in cancer fatalities (4000) in Western Europe among a population base of 350 million; this base includes all Scandinavian and Eastern European countries but excludes a few countries that received the lowest doses, such as Spain and England. The DOE report predicts a 0 to 0.018% increase in fatalities (0 to 13,000) throughout Europe in a population of 400 million. This report also predicts that 96% of the health effects from Chernobyl will occur in Europe and the USSR. Health effects in the United States are expected to be negligible.

It is important to recognize that the transport and dose-effect models conservatively assume that no food management or cleanup would take place. But, in fact, in the Soviet Union major dose-reduction efforts have been undertaken and may be needed for several years, including decontamination, topsoil removal, food and livestock monitoring and destruction, and agricultural restrictions. In Europe large amounts of foodstuffs were destroyed, and much food was eliminated from consumption that had contamination levels below the threshold for recommended protective action. An important point that must be understood with regard to these health effect predictions is made by Robert Catlin of EPRI's Energy Study Center: "Despite the massive releases of radioactivity and the high on-site health toll, there probably won't be any demonstrable health effects outside the USSR. Health effects estimates would range down to zero with the low doses received outside the Chernobyl evacuation zone." □

duce any detectable effects."

The questions surrounding this accident will not necessarily be entirely confined to the Soviet Union, we are reminded by Walter Loewenstein, deputy director of EPRI's Nuclear Power Division and coordinator of the Institute's international Chernobyl response activity. "I won't call it a lesson, but one of the messages of Chernobyl is that a serious accident anywhere is a serious accident everywhere. One result is that international protocols are emerging in accident notification, information exchange, and, to some extent, safety standards, very much like we have in air traffic safety," says Loewenstein.

Floyd Culler says that this international focus will take on a larger role in EPRI's research on nuclear power. "We will certainly be more deeply involved with the IAEA, but it's likely we will also be working more closely with individual countries on safety matters to better understand how to manage an accident if it occurs and, most of all, to learn more about the effects of radiation exposure on people." Loewenstein adds, "There is probably a limit to what we as an industry can do internationally. Through international organizations, we can broaden our perception and ensure that the steps being taken are in the right direction. But the industry in this and other countries must take greater initiative than in the past on steps toward overall excellence."

Research continues

"Complacency is the worst enemy of nuclear power, just as it has been for other industries," says Loewenstein. "Every accident in this business, just like every commercial airline accident, prompts a new look at some old problems. We've learned some lessons as a result of TMI, and Chernobyl will offer some insights, too. We are addressing these insights in our research program."

Immediately after the accident, EPRI nuclear analysts were in touch with European contacts; they quickly amassed all available technical information on Soviet RBMK reactors and extensively analyzed their safety, as well as every detail of the Chernobyl accident. There is now a relatively good understanding of the accident and its causes. Although it has been concluded that the type of accident that occurred at the Chernobyl RBMK could not happen in Western-design LWRs, this does not invalidate the need for further work.

New perspectives on research needs are largely a matter of emphasis—defined not so much by a group of scientific unknowns, as by some well-defined technical tasks that require more intensive study. As for the subjects likely to see increased research attention, Floyd Culler says, "I think EPRI will focus more attention on problems of dosimetry and radiological health effects. We will try to involve the biological and medical communities more fully than in the recent past. Educating these professionals at large about radiation in severe accidents is important. Research on radioactive transport and cleanup procedures will also receive increased attention.

"In the design area, the principal challenge centers on containment integrity and the appropriate level of design against severe accidents," notes Culler. To the extent that containments are a major defense against environmental release in severe LWR accidents, questions about their ultimate strength become more prominent. "The top half of the Chernobyl reactor plant was essentially uncontained and permitted virtually unrestricted release to the environment once the reactor vault was breached by overpressurization," observes NSAC's Gary Vine. Many experts conclude that an LWR-type containment, had it existed at Chernobyl, would have greatly limited the radioactive release and off-site consequences.

"People inevitably ask, couldn't it happen that you have severe core damage leaking massive amounts of radioactivity and then have a containment failure?" notes John Taylor. "You have to say there is a remote possibility of that—you never say never—but all the evaluations show that it takes days for a containment to even begin to fail—that is, to leak—by which time the intensity of the release is greatly reduced." American LWRs are leak-tested at 1.15 times the design pressure before being operated. Extensive U.S. and West German testing of containment overpressure capacity suggests ultimate capabilities of 1.7 to 5 times the design strength; realistic failure modes would involve small leaks rather than gross structural failure.

PERHAPS THE GREATEST EFFECT of Chernobyl on U.S. nuclear power will be in the areas of source terms (the composition, magnitude, and timing of radioactive releases) and emergency planning zones. In terms of radioactive release, the Soviet accident was "about as bad a nuclear power plant accident as one can imagine," says Richard Vogel, senior scientific adviser in EPRI's source term program. "How serious was it? Some idea can be obtained by comparing Chernobyl and the Three Mile Island accident. The Soviets estimated that over 7 million curies of the short-lived radioiodine were released at Chernobyl, in comparison with 10–20 curies at TMI." Estimates of the radiocesium released from Chernobyl range from 1 million to 2.5 million curies; at TMI, in contrast, no detectable cesium escaped the plant.

Utilities and local and state authorities must plan for the health and safety of the public, including sheltering or evacuation in the event of an accident with the potential for significant release of radioactivity. The appropriate emergency planning zone around a reactor in this country is strongly based on estimates of credible LWR severe-accident source terms.

After the TMI accident, NRC enlarged the emergency planning zones around most reactors in the United States from a radius of 2–3 miles (3–5 kilometers) to 10 miles (16 kilometers). But the release from TMI turned out to be substantially lower than U.S. safety studies had projected for that type of accident, and also involved better-than-projected chemical retention of fission products in the plant water and inside the containment. In light of these favorable results, EPRI, NRC, and the nuclear and utility industries have for seven years pursued a broad range of research to verify and redefine severe-accident source terms.

The source term research was nearing completion before Chernobyl, with major fission-product release and transport experiments and modeling calculations pointing to substantially lower source terms for severe accidents in LWRs. Public concern over the Soviet accident, however, is sure to make acceptance of this research more difficult.

In two cases operating licenses for plants are being held up because of the refusal of governors to give state approval to utility emergency plans. NRC is now considering a rule change to permit the issuing of operating licenses in situations where local governments decline to participate in emergency planning. The proposal is being strongly opposed by some members of the public because of fears generated by Chernobyl.

Considering the major safety differences between U.S. and Soviet reactors, including the massive concrete and steel containment vessels that enclose LWRs, Chernobyl-related fears seem exaggerated. "We don't see anything from the Chernobyl accident that suggests the path we've been on with source term work is wrong; the justification is simply much less likely to be accepted," says John Taylor. "Now utilities are in the position of having to argue not to enlarge the 10-mile planning zones, rather than arguing to reduce them."

Walter Loewenstein observes, "If you really look hard at Chernobyl and what the impact was, I think we've learned a few things that are rather encouraging with regard to severe-accident consequences. The releases were large compared with anything we generally study, and they were open releases to the environment. Despite these facts, models typically predict more-severe consequences than were actually observed. We believe the Chernobyl data will ultimately demonstrate that our models for source term and dose effects tend to be quite conservative. That should be good news."

"One cannot conclude that there will be no further repercussions from Chernobyl on U.S. nuclear power," Culler observes. "Public sentiment has turned more negative, particularly with the media reporting that long-term cancer deaths are probable. Whether or not nuclear power remains an option in this country will depend to a great degree on the public's continued belief in the basic safety of nuclear technology."

The future of the nuclear option

What will become of nuclear power in the aftermath of Chernobyl? No one can say with authority, for the answer to that question lies in the constantly changing political and economic priorities of dozens of sovereign nations with widely varying sensitivities to public opinion and with distinctly different energy supply realities.

In some countries, such as Britain, the nuclear question has become truly politicized for the first time. In others, such as Italy, Chernobyl has fed an already heated debate. An antinuclear coalition was narrowly defeated in last year's West German elections, but the prospects for new plants there reportedly remain bleak. Sweden has indicated it will accelerate a planned phaseout of nuclear power, supposedly by 2010. Denmark and Finland have expressed misgivings about future plants. Austria has already scrapped one reactor and currently plans to build no more. In South America, Brazil put plans for eight reactors on hold before its default on foreign debt.

Those nations that perceive few alternative energy options, however, already have gone on with the business of providing nuclear electricity with a renewed sense of vigilance and commitment to safety. In France, Belgium, Japan, and other countries that depend heavily on nuclear power and where it enjoys broader public support, there has been little impact. And in eastern Europe, as in the USSR, there will be no nuclear retreat.

In the United States the situation has changed little, with Chernobyl mainly adding to the rhetoric. As Floyd Culler notes, the problems of public perception of nuclear power in the United States will persist in the absence of informed consensus. "Whether or not the technology, with the improvements and the renewed operational vigilance this tragedy has engendered, will be enough to turn around the sharply negative public opinion that now exists requires another kind of research, in which we will not engage. One of the aspects we may work on, however, is the bridge between the technical science and the interpretation of science and technology in terms that allow the public to understand better. With any technology, there is not majority rule. Without a pretty wide consensus that a technology is desirable, particularly in the United States, a minority can control whether or not the technology is applied."

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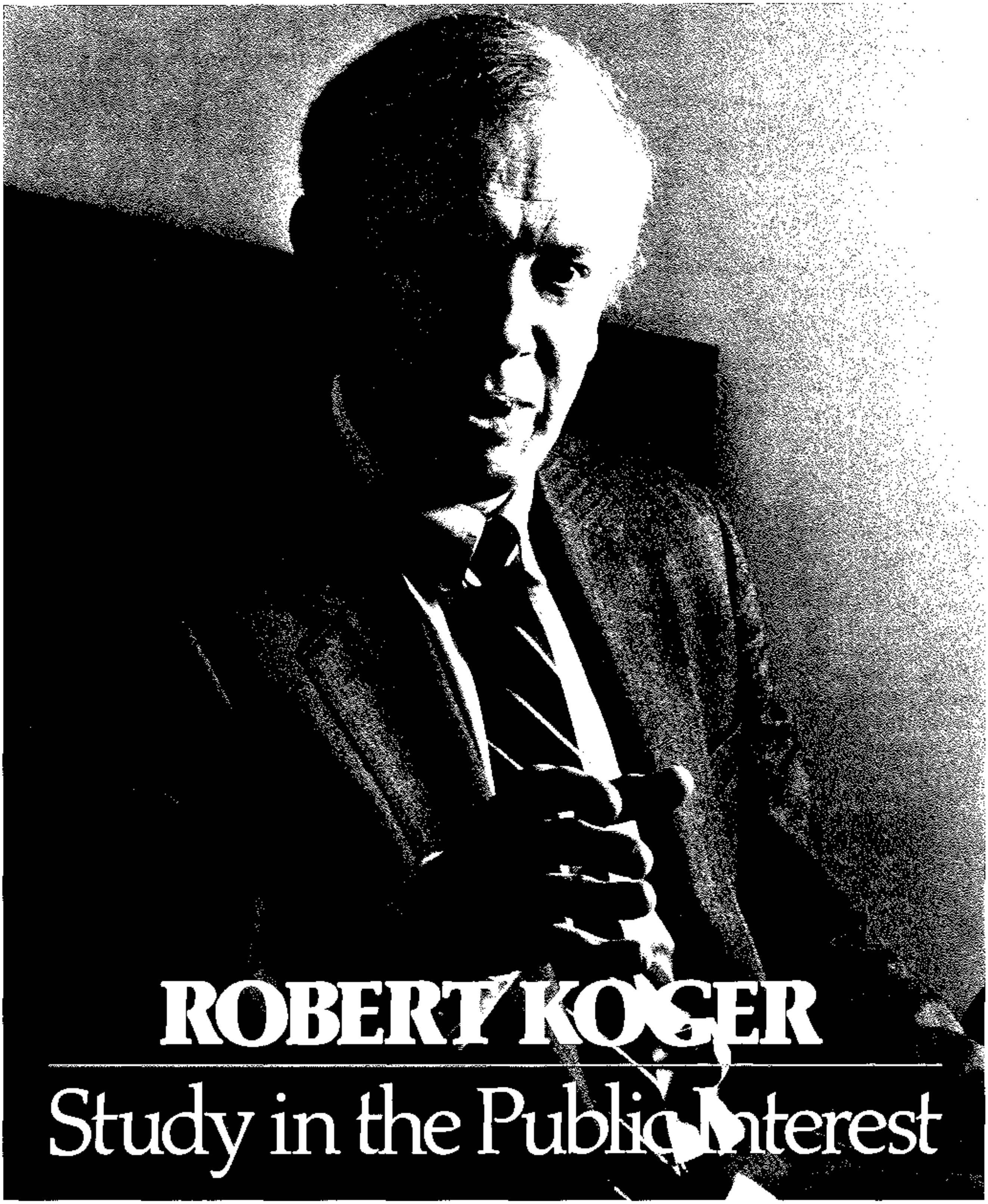
This article was written by Taylor Moore and David Dietrich. Technical information was provided by Walter Loewenstein, Abdon Rubio, John Taylor, Gary Vine, and Richard Vogel, Nuclear Power Division; Leonard Sagan, Environment Division; and Robert Catlin and Edwin Zebroski, Energy Study Center.


ROBERT KOGER
Study in the Public Interest

There is a pattern to Robert Koger's professional life, a methodical, almost rhythmic alternation between the public issues that engage him in his work with the North Carolina Utilities Commission and the personal inquiries that prepare him for what is to come next. His career interests and activities closely parallel the development of U.S. electric utility regulation during the last 20 years.

Formerly a staff engineer for the commission, later its chairman for two terms, and still a commissioner, Robert Koger is by turns a public servant and a student. The two skills combined may yet make him a teacher: in fact, he's already an adjunct professor at North Carolina State University. And after serving eight years on EPRI's Advisory Council, longer than any other member, he would have what amounts to tenure on the Council if the National Association of Regulatory Utility Commissioners (NARUC), which nominated him for membership there, hadn't recently revised its policies.

The Advisory Council consists of more than 20 men and women from many professions, business sectors, and constituencies outside the utility industry. Their individual and collective perceptions give EPRI a useful check on the reality of its own—and the utility industry's—view of R&D direction and priorities. Seven of the Council members are public utility commissioners, named by NARUC for a maximum of two 3-year terms. Koger, however, joined in 1979, when commissioners could remain on the Council as long as they held regulatory office and membership in NARUC; his current term ends in 1989.

Koger's contributions outside of the North Carolina commission go well beyond his concurrent memberships on EPRI's Advisory Council and NARUC's Review Committee for EPRI. He has been on NARUC's engineering committee, becoming its chairman, and he is now on the administration and gas committees. Since 1979 he has been a member of NARUC's executive committee—the position he values most—and he now ranks second in seniority there. He is also a past president of NARUC's southeastern regional affiliate.

> Public service and advanced education have been strong interests for this long-time member of EPRI's Advisory Council. The creative melding of these influences provided Koger with unique preparation for two terms as chairman of the North Carolina Utilities Commission.

With a flash of the inquisitive nature that motivates him, Koger recalls an EPRI connection even earlier than the Advisory Council appointment in 1979. "I was asked to substitute for a colleague at an Advisory Council meeting back in 1975. That's when I got interested, and when an opportunity came up to serve, I volunteered."

Is Council membership therefore really a learning experience, perhaps even more than an advisory one? Koger thinks it is both, and he especially emphasizes the role of new members. "For many of them it's mostly learning, which is extremely important to the electric power industry. They're important people, in a position to influence others, but they probably haven't thought much, before, about the inner workings of utilities."

Then he turns to the contributions of Council members, "particularly the ones who are really outsiders. They come up with fresh ideas readily, much more so than do regulators. We're so immersed in the industry ourselves that we sometimes just don't see."

Finding a place

Asked why he picked electrical engineering at the University of Tennessee back in 1954, Koger is offhand at first. "I was pretty good at math, and it seemed to be the thing to do." Then his memory comes to life. "Once I got into engineering, I liked it very much. I enjoyed studying. Also," he adds, "Sputnik went up while I was in school, in '57, and that was a push."

Koger's first job after graduation was short-lived—"hundreds of us in a huge room; I felt more like a tool than an independent engineer." But even before that feeling matured, a family friend who worked for the Rural Electrification Administration (REA) persuaded Koger to interview there. "It sounded great. I worked three years in Washington, got a lot of training, and then went to North Carolina, to Greensboro, as a field engineer in 1961."

REA was doing much more than rural electrification in the 1950s; it had also organized a telephone loan program and established a separate division to manage it. Koger worked in North Carolina with newly formed telephone utilities—small companies and cooperatives—and their engineers and contractors, ensuring that loan proceeds were correctly applied and systems properly built.

"I liked the work," Koger says without qualification, "and leaving the REA in 1967 was a very hard decision. I was getting interested in doing something else, but I remember turning down the utilities commission the first time." The eventual appeals, he says with a smile, were duty and responsibility; he adds that he was young and impressionable at the age of 31.

He thus joined the North Carolina Utilities Commission as an electrical engineer, one of just three engineers (and two secretaries) on the staff. Two years later he was named chief electrical engineer, and in 1970, when all engineering activities of the growing staff were consolidated in a single division, he became its director.

There were other changes for Koger in the late 1960s. Newly situated in Raleigh with the utilities commission, he nonetheless retained many friendships in Greensboro, made one more friend there in 1968, and married her in 1969. Robert and Jeanne Koger (she's now a biochemist in postdoctoral work at the University of North Carolina) today have twin daughters, 17, and a son, 14—and, as of last winter, a well-used Honda whose operation Koger regulates in the kids' joint interest.

In the course of his work on the commission, Koger began attending meetings of NARUC engineers, and, he acknowledges, he was inquisitive. "I asked so many questions that in 1968 they decided I would be a good person for a new committee on electricity cost allocations, that is, cost-of-service studies.

"Up until then there hadn't been any really major rate cases—electricity had always been a declining-cost industry—so no one was looking into the cost of service." But NARUC, anticipating the need, appointed the head of the power bureau in the Federal Power Commission and the chief engineers of the California, Wisconsin, and North Carolina commissions. Koger is modest about his own selection: "I think they wanted someone young on the committee.

"Because we got into a lot of economic matters," he goes on, "and also because of work I was still doing in telephony, I wanted to know more. So I began to take econ courses at North Carolina State." The committee work evidently benefited from such zeal, as well as from the expertise of others. "With a lot of help we drafted a manual; it was published in 1973, and it's still the standard," Koger concludes.

Koger's graduate education, however, was only beginning. The commission staff workload was on a high growth curve in 1970, but Koger was having little recruiting success. "You couldn't sell engineers on government work; they wouldn't even come to the interviews. So I decided to take some more courses at State and 'breed' a few prospects among the seniors there.

"I recruited economists, too," he goes on. "We were employing outside rate-of-return consultants and paying them $22,000 for one case. I thought we could do better with a staff of our own. The effort built on itself; once you've hired two or three people, they know others to attract." Along the way, Koger by 1973 earned his own MS in economics.

Bringing planning into the open

In 1975 and 1976, Koger says, "several things were interesting to me." His detached comment belies the happy combination of professional curiosity, insightful observation, organizational preparation, and share of good fortune that continued to position him well.

Under his guidance, the engineering and economics staff of the North Carolina Utilities Commission grew to nearly 50 people—far more than the half dozen or so when Koger began. As he talks, there is a hint that his staff was catching up with others elsewhere: "North Carolina is the tenth largest state, and I guess we came into modern regulation during this time. Earlier, our work had been somewhat run-of-the-mill and concentrated in telephony. Now," he observes, "we got caught up in all the turmoil of the electric power industry—the rate increases, primarily, that came from the Arab oil embargo."

There was more to it than that. The state was growing, electricity use was up, and peak loads were becoming a problem. "Because electricity was now an increasing-cost industry, everybody was looking for a way to mitigate that growth. None of us wanted to add plants if we didn't have to."

One response was state legislation, and Koger helped to draft it. "It was comprehensive," he says. "It required the commission to conduct hearings each year and to report to the governor and the state's general assembly on the long-term plans of utilities—I mean, 15 years ahead."

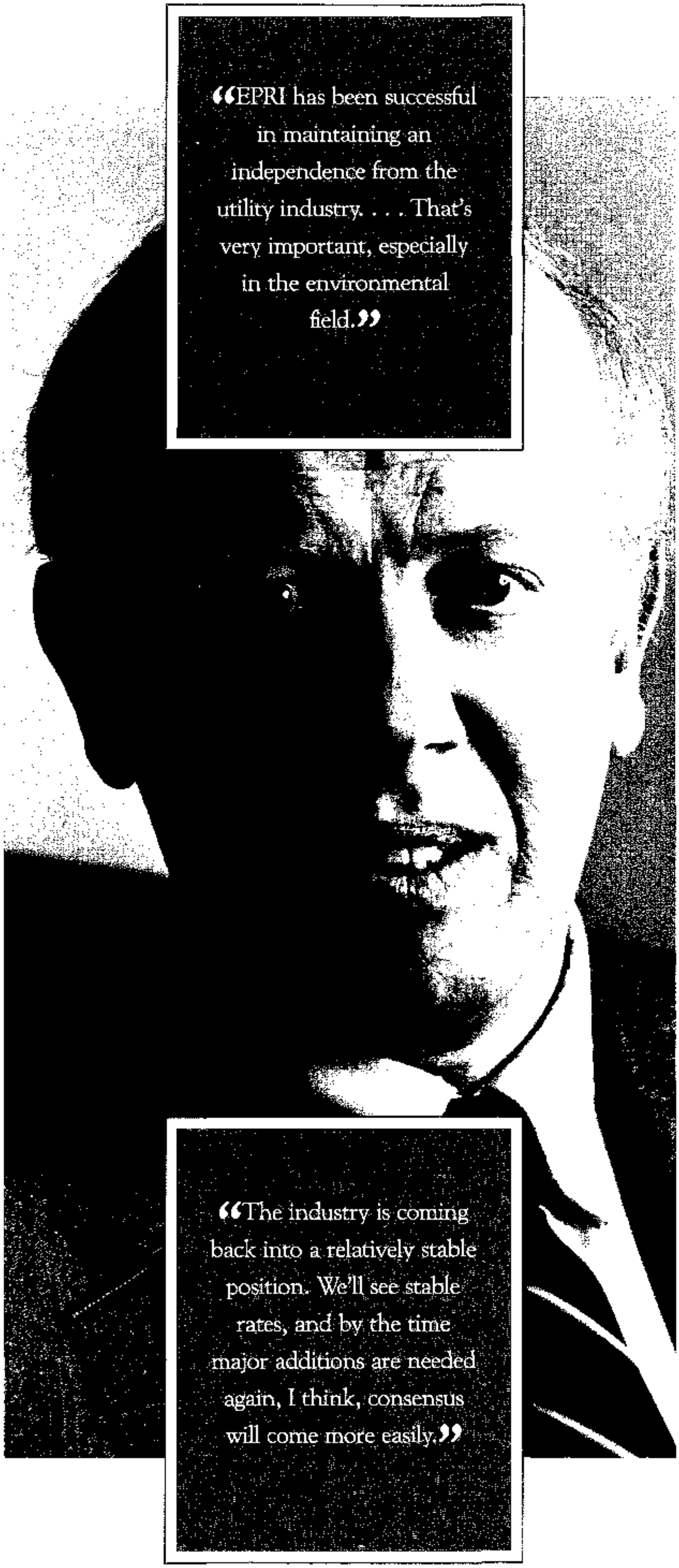
The impact was considerable. "This meant that we, the commission economic and engineering staff, had to come up with our own forecasts. It meant that the utilities had to do a job they could defend in public. Other groups came in with forecasts, too, and they were entitled to be heard.

"All in all, it got electricity planning out in the open. It also put the commission into the position of being partly responsible for the projections—and even for the selection of the plants that would be built."

The confluent forces for planning energy supply and use were more than statewide or regional, of course. They were part of a mainstream of energy management and conservation. They also included a 1974 NARUC resolution that called on EPRI (and the Edison Electric Institute) to examine the technology and costs of peak-load and time-of-day pricing. When EPRI organized its subsequent electric utility rate design study, Robert Koger was selected to head the task force on ratemaking. This was the real beginning of his association with the Institute.

Splitting the commission staff

The organization of the North Carolina Utilities Commission today, and Koger's two terms as its chairman, had their origins in the state election campaign of 1976. The lieutenant governor was already clearly visible in the public give-



and-take over electricity rates. Now, a key point in his successful gubernatorial candidacy was to establish an office on behalf of energy consumers, and to accomplish this by splitting the utilities commission staff into two groups.

Actually, Koger points out, most of the office professionals went to the public staff, as it became known. A far smaller group—including only three or four individuals from Koger's engineering and economic division— continued to work with the state's appointed commissioners and to be known as the commission staff.

With the change in state administration after the election, a number of commissioners resigned, too, and because so many staff members had gone to the public staff, there was a need to ensure expertise and continuity in the commission offices. The new governor, himself a North Carolina State graduate with an MS in economics, knew of Koger through the faculty there. Therefore, in May 1977 Koger found himself accepting appointment to the utilities commission, and he was named chairman two months later.

The concept of separate public and commission staff groups was new in regulatory work at that time, according to Koger, but it has since been adopted in several states. There is irony in the circumstance, because regulatory commissions are rooted in the public interest. Today, however, regulation simply in lieu of natural economic forces is not always synonymous with the public interest, and an advocacy office must be created. Koger sees positives and negatives, "but on the whole I think it's been a definite benefit. People are more confident that somebody is really actively looking after their interests full time."

During 1977, also Koger's first year as chairman, a lot of internal reorganization was needed simply to make the new staff system work. "We needed help remembering to treat the public staff like any other outside party. We couldn't have any contact with them after a case was filed." Losing close communication with known experts was one of Koger's negatives.

This is not to say that the public staff has an adversarial relationship with the commission staff or with the commission itself. "The interaction between the public staff and a utility may be adversarial," Koger acknowledges, "but over all, I think the system enhances the judicial aspect of the commissioners' job. We're the judges. Of course, that means we're criticized by both sides."

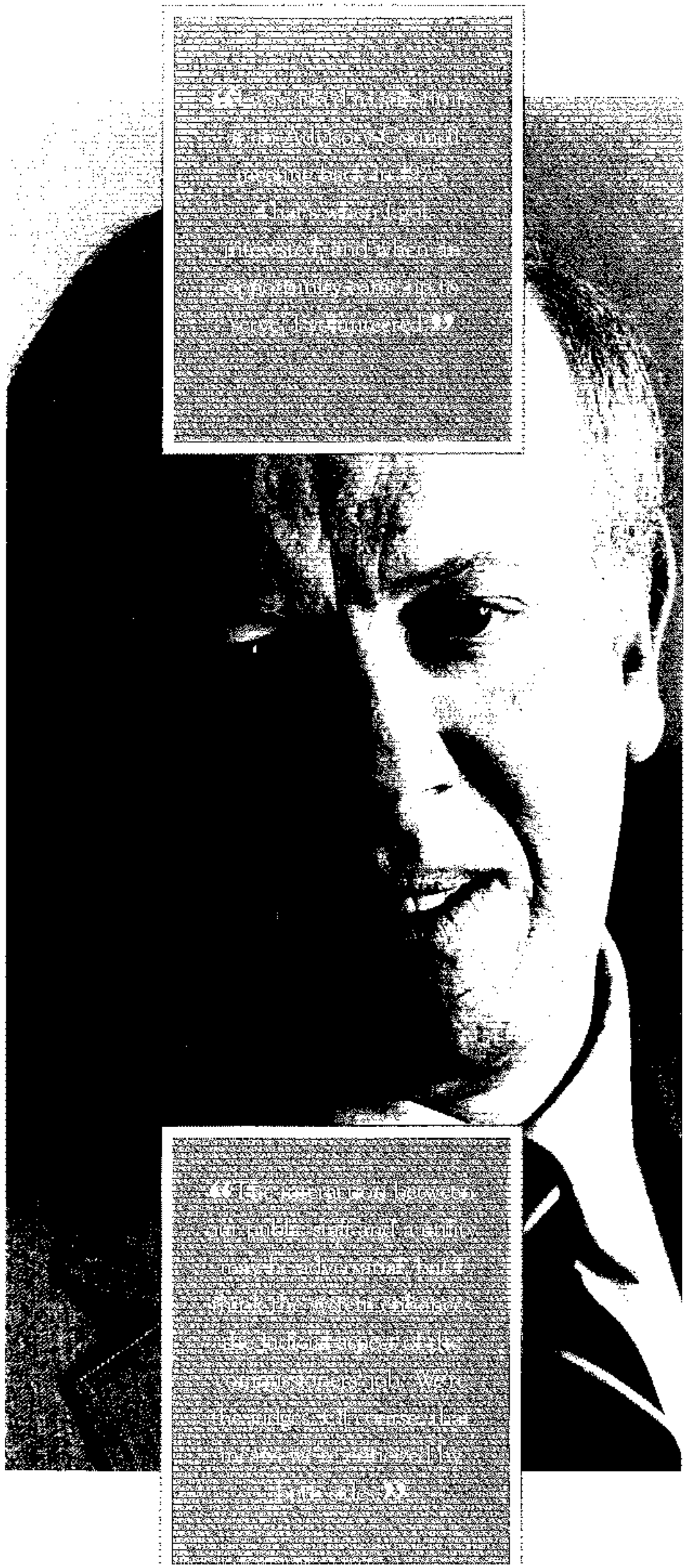
Commission work creates a lot of opportunities for criticism. Koger estimates that there are about 1200 regulated entities in North Carolina—nearly half of them water companies, plus gas, electric, and telephone utilities and trucking companies. "There always seems to be a crisis coming. Late last year people in my own county got Boil Water notices from the health department, so we had to have an emergency hearing on the water system's franchise."

The circumstance makes for a lot of variety, too, and that appeals to Koger. "You've got something different going on all the time," he says. "The only down side is that I don't have the opportunity to get as deeply into some subjects as I'd like. When a telephone matter is pending, for instance, I'll try to immerse myself in the subject for a couple of months, try to learn everything in the area.

"The problem is that I'll be behind six or eight months later, because by then I'm working on something else." Clearly, for a conscientious student such as Koger, the pattern can be frustrating.

Getting educated to advise

But even formal education was not yet entirely behind Koger. After completing his MS in 1973, he had continued in economics courses that interested him. More than that, he listened to friends in industrial engineering school as they discussed their study of management deci-



sion making. He admits he was hooked. "I started taking some of their courses, and they were interesting too. Also, I enjoyed getting back into engineering a little more. So I went ahead, and I finished the coursework for my doctorate in 1977. I didn't know if I'd ever have time to write a dissertation"

The opportunity did arise, quite by chance, in 1981, when a professor at North Carolina's Davidson College asked Koger to be joint author of an NSF-grant-funded study of electric utility pricing. The two worked together for six months, during which Koger realized that electricity pricing was an excellent practical application of decision making and a ready academic topic for his dissertation. He was awarded his PhD in industrial engineering at North Carolina State in May 1984.

Reflecting on his service on the Advisory Council, and on growing utility interest in technology for energy management and use "beyond the customer's meter," Koger thinks also of his state's Alternative Energy Corporation (AEC), conceived in 1979 and launched the following year.

Voluntarily funded by utilities according to their energy deliveries (as is EPRI), the corporation raises some $3 million annually. Koger admits that the sum is modest, but, at a time of great protest over nuclear power, it revealed broad interest in finding other ways to meet energy needs. "We were pleasantly surprised to find that electric cooperatives—which we don't regulate—and municipalities, too, were willing to take part."

The AEC board includes seven public members, appointed by the governor, and six members from utilities. Project committees combine talents from all the utility constituencies, according to Koger—"There must be nearly 300 people in the AEC advisory structure, including many nonutility volunteers.

"Once a year there's an appreciation dinner for everybody involved. As a side benefit, the AEC has made for better operating relationships among electricity suppliers themselves and also between them and some of their former critics."

One AEC initiative was to encourage North Carolina counties to monitor energy uses and identify opportunities for savings. The obvious question mark was the cost—at very least, the salaries of local energy advisers. To establish a win-win outcome, AEC offered to underwrite any salary amounts not met by savings. Has it worked? Koger is emphatic. "Counties have saved thousands of dollars—hundreds of thousands, over all—through the steps they've taken on the recommendations of energy advisers working under AEC sponsorship."

The innovative structure and achievements of the AEC in North Carolina, and its occasional problems, put Koger in mind of his outside professional and advisory associations. He reads the signs of the times, and his curiosity persists. "With all the things that are going on at the federal regulatory level, I think gas could become a hot topic. It's not an active issue with us in North Carolina right now, but it could be very soon, and I want to be prepared. That's why I asked to be on NARUC's gas committee."

Grading the R&D effort

Koger insists that electricity is his first interest. "In priority order, telephone is next, then gas and water, and—way down the list—transportation." The ranking reflects the fact that transportation was not a responsibility of Koger's engineering division during his seven years as its director.

As an EPRI adviser, he notices aspects of how the Institute functions, as well as specific topics. "I think EPRI's work with quite mundane, everyday utility problems is very important," he says, "and certainly reassuring." He cites the example of research into the stress corrosion cracking of piping in certain nuclear reactors, adding, "We've got a couple of BWRs in North Carolina, so I'm very interested in what can be done in water chemistry to improve operating availability by even a few percent. It's many dollars."

Koger gives EPRI good marks also for anticipating problems that utilities might face—environmental control requirements, for example. "I think, too," he says, "that EPRI has been successful in maintaining an independence from the utility industry." By putting most of its research under contract, he feels, the Institute recruits the top people to investigate areas of concern. "You can't assail the reports on the basis of bias, and that's very important—especially in the environmental field."

EPRI's emphasis on short-term R&D—work with an early completion and early payoff for utilities—draws conditional sympathy from Koger, because of today's severe limitations on overall Institute funding. He welcomes a current shift in attitude, however small in dollars, toward longer-term and exploratory R&D. "As DOE funding is reduced, who's going to do the long-term research that's needed?" he asks.

Koger is asked, in turn, whether he is hopeful. "Yes. I guess I'm pretty much an optimist, and there are a lot of positive things happening." North Carolina, at least, is about finished with a lengthy agenda of rate-case work, he says, and utilities there should not need to build additional plants for a number of years. His optimism reaching out even further, he concludes, "I think the whole industry is coming back into a relatively good position. I think we'll see stable rates, and by the time major additions are needed again, I think, consensus will come more easily."

This article was written by Ralph Whitaker and is based on an interview with Robert Koger.

Biotechnology is coming on fast, revolutionizing fields as diverse as pharmaceuticals, farming, and mining. Microbes have been harnessed to produce insulin and human growth hormone. Plant germ plasms have been genetically altered in order to increase yields and pest resistance. And bacteria are now used to mine uranium, gold, and other ores. There's talk of breeding bugs to gobble up oil spills, and lately there's been growing interest in using biologic techniques to improve coal properties.

Bioprocessing of coal is developing along several fronts, each of potential significance to utilities. Through a series of serendipitous events, researchers have found a fungus that can liquefy certain kinds of coal. The implications are potentially immense for a world with dwindling oil reserves, an insatiable appetite for liquid fuels, and centuries of coal supplies. Since new sources of gaseous fuel are also a high priority, one utility is scouring the earth in search of organisms that will biologically convert coal into methane. In relation to the more immediate concerns of air pollution and acid rain, scientists have genetically engineered bacteria that remove sulfur and ash-forming metal impurities from coal.

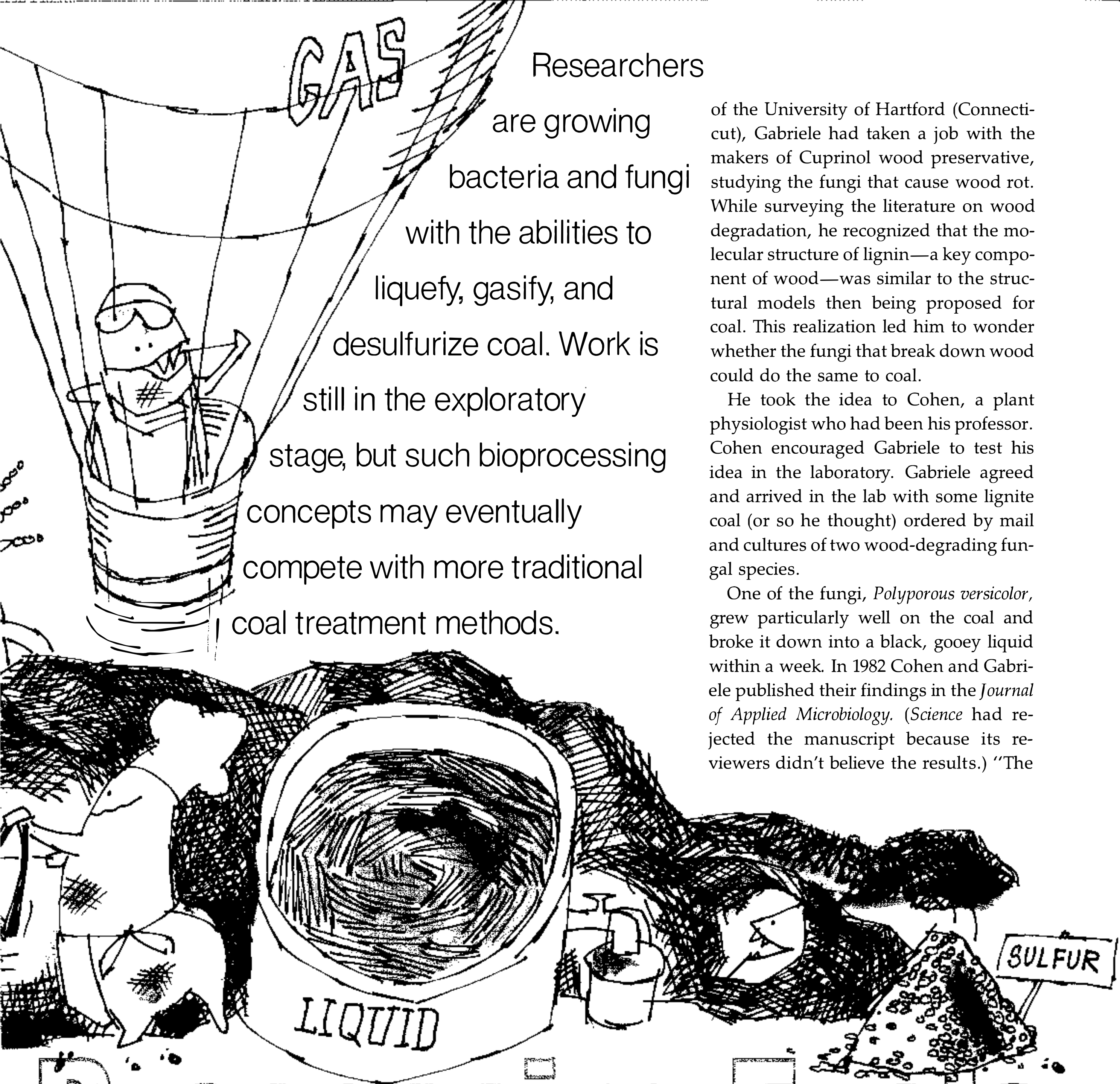
All this work is in its infancy. But so were computers, organ transplants, and dozens of other modern marvels less than a generation ago. And the progress made in some aspects of coal bioprocessing has been so rapid in the past few years that it could be a well-established practice before you can say *Polyporous versicolor.*

Rummaging through God's garbage can

Back in 1981 Martin Cohen and Peter Gabriele had no idea that the simple experiment they were planning would open a new avenue of coal liquefaction research. A recent biology and chemistry graduate

Processing Fuels With Biotechnology

Researchers are growing bacteria and fungi with the abilities to liquefy, gasify, and desulfurize coal. Work is still in the exploratory stage, but such bioprocessing concepts may eventually compete with more traditional coal treatment methods.



of the University of Hartford (Connecticut), Gabriele had taken a job with the makers of Cuprinol wood preservative, studying the fungi that cause wood rot. While surveying the literature on wood degradation, he recognized that the molecular structure of lignin—a key component of wood—was similar to the structural models then being proposed for coal. This realization led him to wonder whether the fungi that break down wood could do the same to coal.

He took the idea to Cohen, a plant physiologist who had been his professor. Cohen encouraged Gabriele to test his idea in the laboratory. Gabriele agreed and arrived in the lab with some lignite coal (or so he thought) ordered by mail and cultures of two wood-degrading fungal species.

One of the fungi, *Polyporous versicolor,* grew particularly well on the coal and broke it down into a black, gooey liquid within a week. In 1982 Cohen and Gabriele published their findings in the *Journal of Applied Microbiology.* (*Science* had rejected the manuscript because its reviewers didn't believe the results.) "The phone really started ringing then," says Cohen. In 1984 he received a grant from DOE to continue and expand the coal liquefaction work. Gabriele's involvement in the research had ended in 1982, when he accepted a new position and left the Hartford area.

In order to understand the biochemical pathways of the coal liquid's formation and to determine what its potential uses might be, Cohen needed to learn something about its chemical structure. "I didn't have the expertise or the expensive equipment needed to analyze the material, so I sent it to a specialist," he explains. "The last thing he told me before I sent him the samples was that this would be a piece of cake. Two months later he sent me a report saying he couldn't figure out what the stuff was made of."

That's the problem with coal," muses Linda Atherton, who manages exploratory research projects at EPRI, "it's God's garbage can and we don't know half of what's in it." Moreover, she stresses, coal's chemical structure is very complex, and no two samples are the same. The fact that coals vary widely proved to be significant in the next stage of Cohen's work.

In 1985 EPRI offered him a contract to collaborate with a team at Battelle, Pacific Northwest Laboratories that the Institute was funding to study biologic coal processing. The partnership proved fruitful. Battelle had the chemical analysis capability and Cohen the biologic expertise and unique success in liquefying coal with fungi.

When the Battelle researchers asked Cohen to liquefy some different kinds of coal, however, he got very mixed results. The fungi that easily degraded the lignite Cohen had been investigating barely grew on some of the other coals.

Mystified by this anomalous result, the researchers tracked down the source of Cohen's coal and found that it was not conventional lignite but a highly oxidized form called leonardite. Tests conducted since then have shown that, in general, coals whose chemical structures are more highly oxidized (either naturally or through chemical pretreatment) are more readily liquefied by the fungus. This finding could be a critical clue in elucidating which chemical bonds are being broken in the bioliquefaction process. Some analysts believe that the key to bioliquefaction lies in severing oxygen-containing ether bonds, which are more prevalent in lignites than in higher-rank coals. Others offer alternative theories about coal's structure and how to break it. That debate is likely to continue for some time.

Whatever the critical reaction(s) may prove to be, chemist Bary Wilson, who heads Battelle's coal-bioprocessing team, observes that if Cohen and Gabriele had not inadvertently tested leonardite rather than lignite in their original research, they might never have had any success in liquefying coal. But they did, and as a consequence the field has advanced extremely rapidly in a few short years.

Speeding the process

The most important breakthrough to come out of the collaboration between Cohen and the group at Battelle, however, was not the identification of the leonardite but the isolation during 1986 of an enzyme that appears to be one of the key agents in the liquefaction process. "The fungus itself takes a week or more to solubilize coal," explains Atherton. "It needs time to grow and establish itself on the coal before producing the solubilizing enzyme or enzymes. A process that slow would never be commercially viable in dealing with large volumes of coal. What we needed was a way to separate the slow part of the process, the growth of the fungus, from the fast part, the enzymatic degradation of the coal. And that's what the work at Battelle has accomplished." Researchers now grow the fungus continuously in a nutrient-enriched bioreactor. They extract liquid from the culture, filter it to concentrate the enzyme, and then apply the enzyme directly to coal, liquefying it in less than an hour.

The resulting product is a dark, water-soluble liquid. Its water solubility poses some challenges and some opportunities. The liquid does not mix with petroleum-based fuel and hence cannot be used as a fuel in its raw form. However, according to Howard Lebowitz, manager of EPRI's Fuel Science and Conversion Program, "it should be easier to further process and refine the coal in solution with water. Conventional coal liquefaction uses the same generic approach but dissolves the coal in organic solvents rather than water. Another nice thing about the biologic approach is that the dissolution takes place at ambient conditions rather than under high temperatures and pressures."

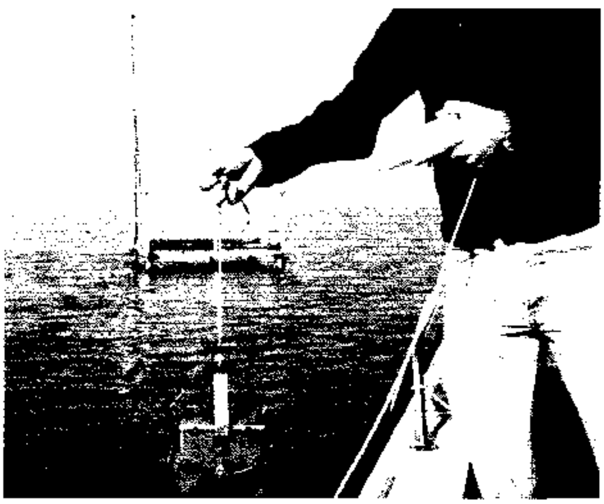
The coal liquid's energy content (by weight) is roughly 95% of the original coal's. One gram of coal does not yield one gram of the liquid, however, and researchers have not yet determined how much of the coal turns into product and how much is taken up by the fungi or converted to gases that escape the reactor. "The question of yield is important," comments Ron Wolk, director of EPRI's Advanced Fossil Power Systems Department. "We really won't know if this process has commercial potential until we get a better handle on how much useful product can be generated from a given quantity of coal."

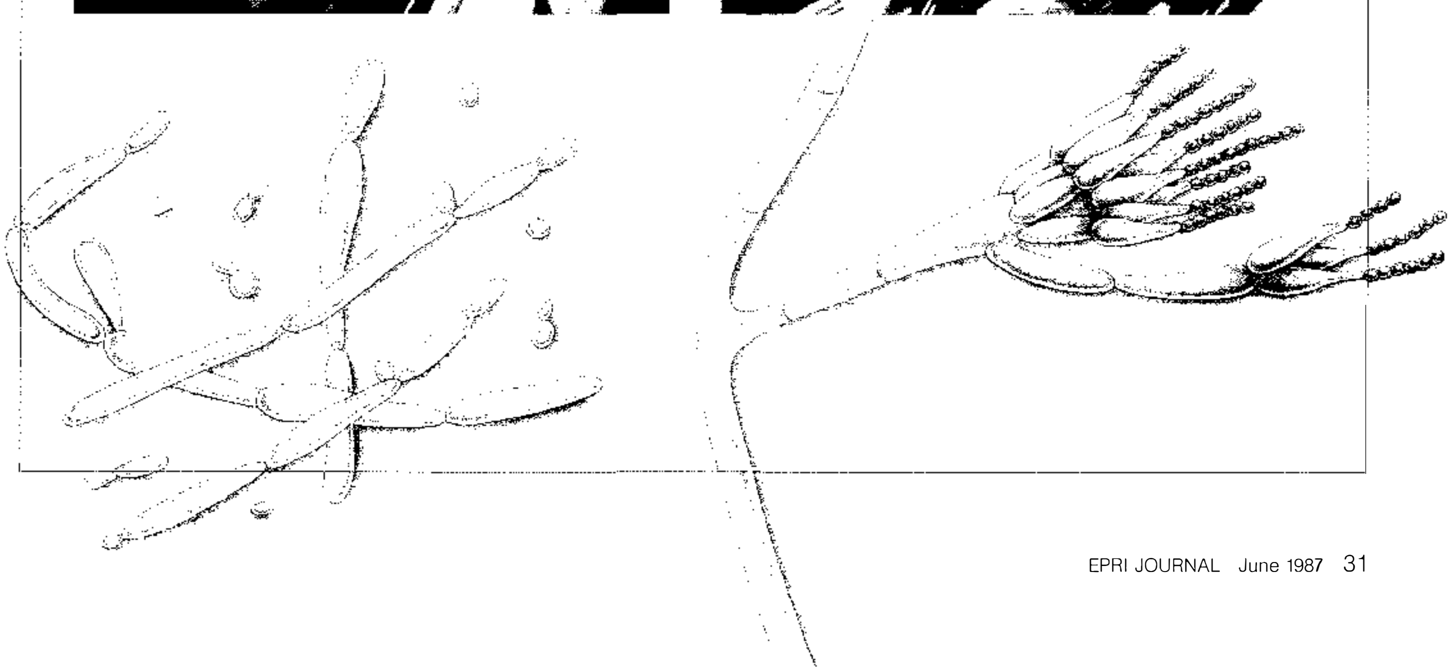
Cohen, Wilson, and the research team at Battelle are exploring the yield issue and a number of others in ongoing work. They are testing other coals and other organisms, are trying to isolate additional enzymes that may contribute to solubilization, and are applying enzymes to model compounds of known chemical structure to try to understand the fundamental reactions that break down the coal. Their work has stimulated other in-

Searching for Microbes

Scientists are searching in a variety of places, from rotting logs and weathered coal seams to the bottom sediments of the Great Salt Lake, for microbes that will modify coal. A number of bacteria have been identified that will convert coal to a gas or remove its sulfur. Genetic engineering has been used to enhance the effectiveness of sulfur-removing bacteria. Several fungal species will liquefy certain kinds of coal, particularly lignites. Enzymes isolated from one coal-liquefying fungus act much faster than the fungus itself, raising the potential for commercial viability.

Seeking salt-tolerant bacteria in the Great Salt Lake





vestigators throughout the country. Biologists are scouring old coal seams for coal-degrading fungi and bacteria. (Bacteria are good to work with because they grow much more rapidly than fungi.) Chemical engineers are extrapolating from reaction rates in laboratory experiments to project whether bioliquefaction of coal is viable at commercial scale. And economists are taking a hard look at the costs and benefits of such processes.

The field has its skeptics as well as its champions. They all acknowledge, however, that tremendous strides have been made in the few short years since Gabriele and Cohen stood over a petri dish and watched a mat of fungus liquefy a few lumps of coal. And all the activity in liquefaction is only one part of a broader attempt to improve the properties of coal through biologic processes.

It's a gas

While Cohen and others study bugs and fungi that liquefy coal, Houston Lighting & Power Co. is looking for organisms that will convert lignite directly to gaseous methane. "HL&P uses a lot of natural gas and wants to find some alternative fuels," explains Ernest Kern, a chemical engineer in the consulting engineering department at the utility. "We have a lot of lignite in Texas, so we decided to look at the possibility of gasifying it with microbes. Since it would be too expensive to build above-ground stainless steel fermenters for the kinds of volumes we would need, we started looking for cheaper reactor options."

The utility decided to explore the notion of carving out a large cavern in an underground salt dome to serve as a lignite digester. "That would be fairly easy," says Kern. "Then we'd just grind up the lignite, mix it with water, stir in some bacteria, and pour the slurry into the salt cavern, where the bugs could go after the lignite. The hard part is finding a bug that will eat lignite in a salty environment, doesn't breathe oxygen, and excretes methane."

HL&P is looking. It hired Dynatech Scientific, Inc., to help it track down methane-producing organisms in some pretty strange and salty places. The researchers have gathered microbes from bottom sediments in the Dead Sea and Utah's Great Salt Lake. Professor Holger Jannasch of the Woods Hole Oceanographic Institute provided them with bacteria gathered from thermal vents on the ocean floor off Mexico's Baja peninsula. They have even helicoptered to offshore oil rigs in the Gulf of Mexico to scrape the slime off underwater filters used in oil production.

Dynatech has cultured these organisms in its Cambridge, Massachusetts, laboratories and has found that several strains do produce methane from lignite. This year studies of the microbes will continue in bench-scale bioreactors up to 10 liters in volume. According to Kern it is too early to say what kind of gas yields could be expected from a full-scale lignite gasifier, but he suggests that such a facility would produce a lot more than methane. "We've done some conceptual designs for a lignite refinery that would produce a number of products—including benzene, toluene, and xylene liquid fuels, organic acids for chemical feedstocks, and carbon dioxide, in addition to methane for our boilers and combustion turbines. We hope that such a process will produce gaseous fuel for us more economically than the high-temperature and -pressure coal gasification systems now being developed."

You'll wonder where the yellow went

Not everyone wants to turn coal into a gas or liquid, but with air quality and acid rain control high on the national agenda, many researchers are trying to find ways to remove pollution-causing sulfur from coal before it is burned. Physical coal-cleaning methods remove some of the pyritic sulfur particles that exist in coal as distinct veins or nodules, but they do not remove the organic sulfur that is bound chemically into the coal molecules. More than half of the sulfur in some coals is in organic forms.

When coal is finely ground for physical cleaning in a froth flotation system, the small pyrite particles tend to be repelled by water and thus float with the coal rather than sinking with the other impurities. Several investigators, including Jenefir Isbister, a microbiologist at Atlantic Research Corp. in Alexandria, Virginia, are evaluating the use of a bacterium called *Thiobacillus ferrooxidans* to enhance the physical removal of pyrite. Isbister reports that if the ground coal is pretreated for 15 minutes in a rich broth of *Thiobacillus*, by-products from the bacteria adhere to the pyrite particles and change the particles' surface properties so that they sink more readily in the flotation chamber.

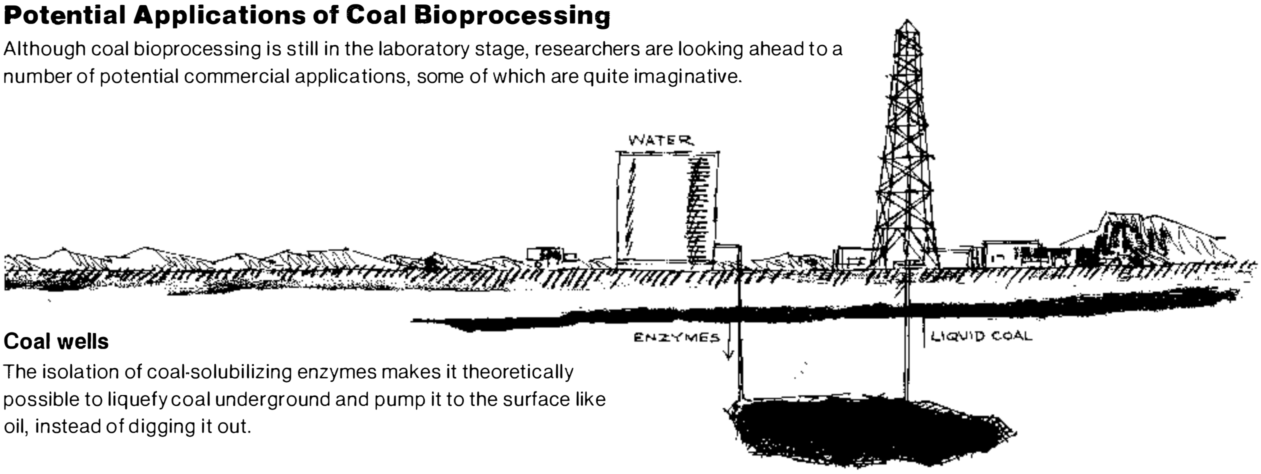
"Such a biologic surfactant process may be an excellent complement to physical cleaning," says Isbister. "All it requires is a tank for treating the coal before it enters the flotation cell. The cost would be relatively modest, and the results we're getting in the lab are encouraging. In some tests the surfactant doubles sulfur removal."

Isbister stresses that while enhancing pyritic sulfur removal is important, it is not sufficient if the industry is to meet more stringent sulfur emission standards without the use of scrubbers. "We have to remove some of the organic sulfur as well," she asserts.

She approached the organic sulfur problem by trying to grow *Pseudomonas* bacteria on dibenzothiophene (DBT), a model compound that is believed to be structurally similar to the most prevalent form of organic sulfur in coal. "Initially the bugs didn't like it, but we did a few mutations and selections and wound up with a strain, dubbed CB1 (coal bug 1), that would tolerate pretty high concentrations of DBT. Then we treated coal with the microbes, and they actually removed organic sulfur. It takes a while, but we've got it down from 12 hours to 9 hours by grinding the coal so the

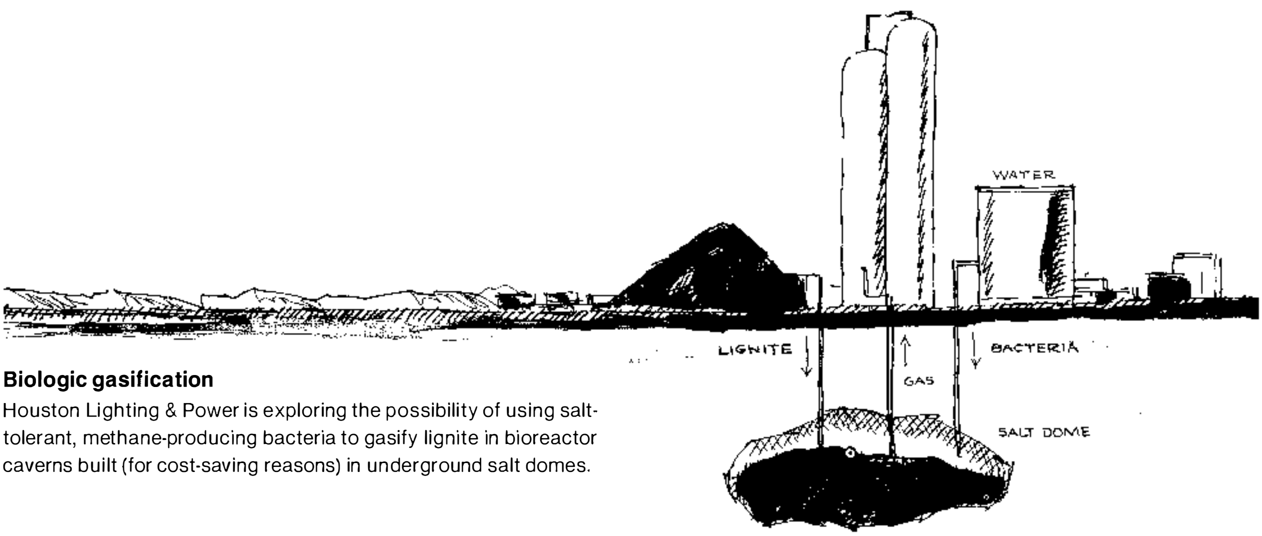
Potential Applications of Coal Bioprocessing

Although coal bioprocessing is still in the laboratory stage, researchers are looking ahead to a number of potential commercial applications, some of which are quite imaginative.



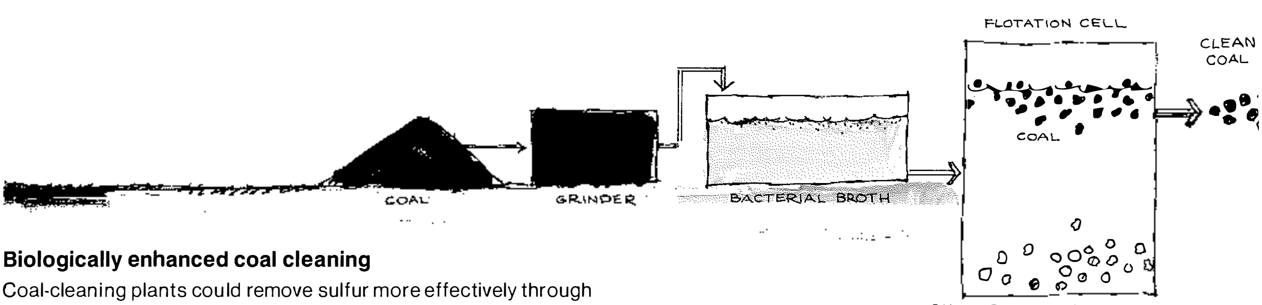
Coal wells

The isolation of coal-solubilizing enzymes makes it theoretically possible to liquefy coal underground and pump it to the surface like oil, instead of digging it out.



Biologic gasification

Houston Lighting & Power is exploring the possibility of using salt-tolerant, methane-producing bacteria to gasify lignite in bioreactor caverns built (for cost-saving reasons) in underground salt domes.

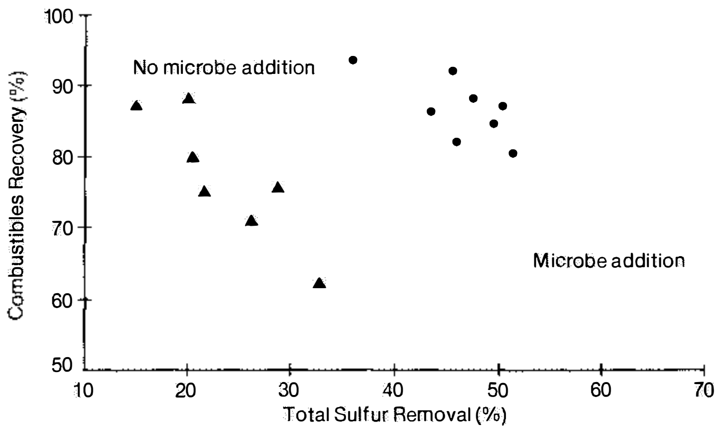


Biologically enhanced coal cleaning

Coal-cleaning plants could remove sulfur more effectively through biologic pretreatment of finely ground coal.

Bacteria Double Sulfur Removal

Thiobacillus bacteria alter the surface properties of sulfur-containing pyrite particles, causing them to sink with other impurities rather than float with fuel particles in a coal-flotation cleaning chamber. Total sulfur removal is doubled with the microbial treatment while recovery of the coal's combustible material remains high, at 80–90% (graph). A genetically altered strain of *Pseudomonas* bacteria removes organic sulfur by breaking sulfur bonds in the coal's molecular structure.



Thiobacillus

Pseudomonas

bugs can get at the sulfur more readily. With a little more process optimization, we hope to cut the time needed even further."

Isbister is currently experimenting with a mixed culture of CB1 and a new strain (CB2) and reports that the two bacteria working together remove organic sulfur more efficiently than CB1 alone. "Our goal is to be able to biologically remove 60% of the organic sulfur from coal. If we can do that and combine it with biologically enhanced physical pyrite removal, then many major coals could meet stricter emission standards without the need for expensive scrubbers on power plants."

Isbister explains that a number of other groups, including Pennsylvania State University, the University of Georgia, IGT Inc., Southern Illinois University, and the University of Kentucky, are working on organic sulfur removal, but most are being fairly secretive about their methods and results. "We all have a common goal, to develop a process that will remove organic sulfur economically, efficiently, and reliably. And we all face the same challenges."

The first challenge she cites is the heterogeneity of coal. "We may never find anything that will treat every coal known to man. We have to tailor our treatment process to the coal." That may mean different bugs for different coals, because microbial strains vary just as coals do and a bacterium that works poorly on one coal may perform well on another.

The stability of microbial cultures is another concern of Isbister's. "We are talking about genetically engineered organisms," she explains, "and some of them are not notably stable for extended periods of time." To make sure that her bacterial strains are not losing their appetite for sulfur through the generations, Isbister tests her bugs regularly on samples of a coal that she stores under special conditions to prevent oxidation and other changes.

Another problem she sees is that the process is still too slow. "Even nine hours is much too long," she says. "It's much better than a few days, but that's all relative. The people in the coal field want rapid turnaround. They don't want huge holding tanks tying up their coal for a long time. This is an area we really have to address in process optimization.

"We have a long, hard row ahead of us. But we have to be ready when people are willing to try this technology for whatever reasons—whether the price of oil goes through the sky, or the sulfur emission regulations change and industry doesn't want to put scrubbers on everything. With luck and hard work, maybe we can make bioprocessing of coal a real alternative in the next decade."

Economics in question

Whether or not biologic coal processing will be economically viable remains to be seen. Economist Jerry Jones of SRI International has his doubts. "Most of the money being invested in biotechnology is aimed at high-value, low-volume products in the fields of medicine, agriculture, and specialty chemicals." Jones explains that biotechnology R&D is very expensive and that the firms in the field aim for products with high potential profit margins to help pay off the R&D costs. He points to human growth hormone produced from genetically engineered bacteria as an example. Worldwide production is about 1 kilogram a year, it costs about $6000 a gram to produce, and it sells for about $40,000 a gram.

Coal by contrast is a high-volume, low-value product. U.S. utilities pay about $30 a ton for the roughly 700 million tons of coal they burn every year. Any economically viable processes for cleaning or converting coal must be relatively inexpensive. Biologic sulfur removal, for instance, must compete with flue gas desulfurization, which costs about $17 per ton of coal burned.

The cost of biologic processing, however, will depend on the advances made in the coming years. If the pace of progress continues as it has in the last five years, reaction rates may increase dramatically and processing costs will drop accordingly. The use of mixed biologic cultures containing several kinds of organisms also may bring costs down by conducting two processes, like biolique-faction and biologic sulfur removal, simultaneously.

The age of biology

"It is clear to me that we are entering the biologic age," states Dwain Spencer, EPRI's vice president for advanced power systems. "Although many questions remain to be resolved, the exciting progress that has been made in a few short years convinces me that biologic processing systems for coal will be an important element of the electric utility industry's future. It won't be easy. The low value of coal means that processing costs must be kept low. A lot more data on mass and energy balances are needed, and a far better understanding must be demonstrated of what the yields and conversions really are. But I'm confident that our research program will lead us to answers for these questions. EPRI has a serious commitment to the development of a biologic processing capability that will give the industry far greater flexibility in its search for clean, economic ways of utilizing coal." ■

Further reading

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This article was written by Michael Shepard. Technical background information was provided by Linda Atherton, Advanced Power Systems Division.

TECH TRANSFER NEWS

TOMCAT and Its Champion

Product champions are rare individuals. Combining creativity, persistence, and vision, they often see opportunities that others don't and undertake the difficult task of selling their peers on new ideas and better possibilities for the future. Years later, when the product of that vision—often called progress—appears to have been inevitable, the world tends to forget the role played by these visionaries. Joseph M. Van Name, superintendent of the Overhead Transmission Section of Philadelphia Electric Co., is a product champion: indeed, the product TOMCAT is his creation.

The idea for TOMCAT (teleoperator for operations, maintenance, and construction using advanced technology) originated in 1976 when Van Name was in Norway to attend meetings of the International Electrotechnical Commission (IEC). Van Name, now international president of IEC Technical Committee 78, Tools for Live Working, was at Trondheim and Bergen and observed how remotely controlled devices operated underwater in the North Sea oil fields. If a manipulator could function in that harsh environment, he thought, why not try something similar for transmission line repair? With such a device utility crews would no longer be exposed to live-line hazards and to the elements, and repairs could be made regardless of high winds, ice, snow, temperature extremes, and other natural phenomena.

Van Name soon discovered that General Electric's King of Prussia facility, located a few miles from his own office, had manufactured the manipulator observed in Norway and that one such device was at the GE factory for maintenance. Arranging to borrow the manipulator to test his idea, Van Name had Philadelphia Electric mount the device on a bucket truck and rig a television camera as a mock-up monitor. The utility quickly saw that two people using this device could do work normally requiring a crew of four, and that the work could be done in poor weather.

Excited about the possibilities, Philadelphia Electric and a group of other utilities formed a consortium and contracted with General Electric to produce the device. As the utility group discovered, however, there was an overwhelming legal obstacle to this relationship. GE Canada had been awarded the contract to build a manipulator arm for the Challenger space program, and after due consideration GE decided that it would not be able to work on the utility project.

Van Name

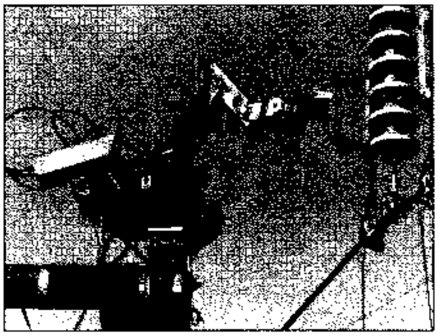
Because so many utilities had become interested in this project, Philadelphia Electric wrote the specifications and brought them to EPRI in 1981. EPRI cofunded TOMCAT, with Southwest Research Institute serving as the contractor, Kraft Ocean Systems producing the manipulator, and A. B. Chance Co. providing commercialization services.

The result of this effort—TOMCAT—is a remotely controlled manipulator with robotic capability. In its basic mode it duplicates the human controller's movement, with the same degree of freedom as the human hand and with continuous wrist rotation. TOMCAT does not need a ratchet wrench; it turns sockets directly and continuously. The Kraft-designed manipulator also has limited robotic capability. This means that in the programming mode, once TOMCAT has completed a movement or operation, it can remember the required movement and repeat it—either forward or backward—on command. The prototype has already proved its mettle in a demonstration of insulator changeout on an energized line and in cleaning transformers at Philadelphia Electric's Peach Bottom nuclear plant.

TOMCAT has lived up to Joe Van Name's original dream, but this dream has already expanded. He believes that "Tommy's" applications are almost limitless, depending only on the ingenuity of the user. Because the device had originally been designed to operate underwater, it can work safely in water-filled manholes or in other wet environments.

Van Name pointed to two recent situations where a completed TOMCAT system would have saved time and provided safer working conditions for the repair crews. In one case a line had been out of service for five days because high winds, ice, and extreme windchill factors had produced conditions too hazardous to risk using service crews. With Tommy, the operator would have been safely ensconced in a warm truck cab as much as a mile away while the manipulator performed the necessary repairs.

In the other example an oil tanker had struck a tower in the middle of a river, damaging its support of a 500-kV line. Repairing this tower was an extremely dangerous job, and the danger was compounded by the necessity of performing the initial inspection at night. If TOMCAT had been available, repair crews could have used it from shore to focus a spotlight and inspect the top of the 450-foot tower—very important functions and very dangerous jobs for human crews.



Van Name realizes that any new technology will need some time to become accepted. In fact, he recalls that in the 1950s, many utilities never dreamed that they would have a bucket truck for each crew—they thought the trucks would be too expensive. Now bucket trucks are a given, a fact of utility life. Van Name sees that same future for TOMCAT, and it will cost less than an aerial bucket truck. Eventually, he expects, all utilities will have one or two Tommies to use in all facets of utility work, and he sees Philadelphia Electric as a driving force in the training of TOMCAT operators. *EPRI Contact: Richard Kennon (415) 855-2311*

Demand-Side Planning: Twelve Years of R&D

Since its inception in 1974, EPRI's Demand-Side Planning Program has conducted more than 120 research projects and produced more than 230 publications, computer codes, and other products. A new report, *Demand-Side Planning Program: Projects and Products, 1974–1986* (EPRI EM-5062-SR), provides utilities with a record of all research undertaken by the program and lists all the resulting products. The report is divided into three sections: end-use assessment and forecasting, planning and information, and marketing support.

During the first few years, the program's research focused on issues of electricity use and forecasting at national and regional levels. Later the program was expanded to include rate design and load management issues; the resulting research helped crystallize industry thinking on marginal-cost pricing and produced the first comprehensive reference material on load management. The program's current research concentrates on forecasting, planning, and marketing issues that can be addressed by utilities at the service-area level. *EPRI Contact: Clark Gellings (415) 855-2610*

Guide to Advanced Ultrasonic Testing Systems

Utility engineers typically use manual ultrasonic testing methods for preservice and in-service inspections of BWR piping. In recent years, however, automated (advanced) ultrasonic systems have proved more reliable for the detection of some defects, such as intergranular stress corrosion cracking.

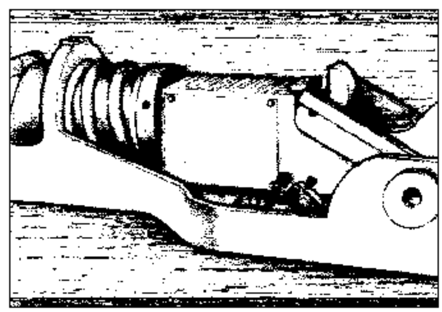
For current information on these automated systems, utility engineers can turn to the *Utility Guide to Advanced Ultrasonic Systems for Preservice and In-Service Inspections* (EPRI NP-5086). This resource explains the concepts involved in using the systems, discusses the potential cost savings and benefits they offer, and presents criteria for specifying and purchasing them.

Cost analyses prepared for the guide indicate that the effective cost of advanced ultrasonic inspection is about half that of equivalent manual techniques. The guide's listing of available systems provides utilities with a basis for estimating quantitative cost-benefit ratios for both types of system. *EPRI Contact: Michael Avioli (415) 855-2527*

Maintenance Techniques for Fossil Fuel Boilers

More than half of the $4 billion that utilities spend annually on fossil fuel plant maintenance is directed at boilers and auxiliaries. Utilities taking steps to reduce this expense through the implementation of new tools and methods can find information in a new EPRI report, *State-of-the-Art Maintenance and Repair Technology for Fossil Boilers and Related Auxiliaries* (CS-4840).

The report documents techniques for the fast and economical completion of 18 important tasks, including the repair and maintenance of boiler tubes, air heaters, ash hoppers, burners, expansion joints, pulverizers, and sootblowers. The techniques pertaining to each task are explained in the text and illustrated with photographs and diagrams. A bibliography and a list of technical contacts are provided for obtaining additional information.



By documenting the current state of the art in boiler maintenance techniques, the report can be valuable to power plant personnel as both a reference and a training manual. At the same time, it provides the electric utility industry with a baseline for evaluating the merits of techniques developed in the future. *EPRI Contact: David Broske (415) 855-8968*

R&D Status Report
ADVANCED POWER SYSTEMS DIVISION

Dwain Spencer, Vice President

SITING CAES PLANTS

Compressed-air energy storage (CAES) is a modular, environmentally acceptable, and fast-responding energy storage technology. A 290-MW plant has been operating in West Germany for nine years, and a 25-MW plant was commissioned in Italy last year. Alabama Electric Cooperative, Inc., and EPRI plan to build and operate the first U.S. plant (50 MW) by 1990. Despite the technical success and attractive economics of CAES, many utilities are concerned about the viability of storing air underground. Many of the concerns can be resolved by using the vast experience of the natural gas and petroleum industries in underground gas and oil storage. This status report summarizes EPRI research aimed at resolving generic air storage issues and helping utilities evaluate air storage media at their respective sites.

A CAES plant is a hybrid of a simple-cycle gas turbine power plant and an energy storage plant. In a CAES plant a clutch decouples the air compressor and the turbine from the motor generator so that each can operate separately. During off-peak periods compressors are driven by the motor generator, and compressed air is delivered to an underground storage reservoir. During peak and intermediate-demand periods, air is withdrawn from the storage reservoir, heated, and expanded through turbines to generate power.

CAES plants offer several benefits. They enable utilities to make the best use of existing baseload plants and to reduce reliance on expensive fuels for providing intermediate and peak load capacity. During compression a CAES plant uses about 0.75 kWh of off-peak energy per kWh of output. During generation it uses about 4000 Btu of oil or gas per kWh of output; in comparison, conventional gas turbines use 12,000 Btu per kWh. CAES plants produce about one-third the emissions of a typical combustion turbine. Because they are modular, CAES plants reduce financial risks; utilities can add relatively small units (25 to 100 MW) to match load growth. The plants' quick-response capabilities offer advantages in terms of system regulation and spinning reserve. All these benefits improve overall system operation and generating-unit efficiencies.

The compressed air for a CAES plant is stored either in man-made excavations in salt or rock formations or in naturally occurring porous rock media. Plant siting requires favorable geology for the air storage reservoirs as well as acceptable location. Potential sites with either new or existing underground storage space are grouped into three geologic categories.

- Rock caverns created by excavating hard rock formations
- Salt caverns made by solution and dry mining of salt formations
- Porous-media reservoirs made by water-bearing aquifers or depleted gas or oil fields

An EPRI-sponsored analysis of state geologic surveys determined that about three-fourths of the United States could provide potential CAES sites (*EPRI Journal*, December 1983, p. 61). A few site-specific studies have determined the siting feasibility of CAES plants using rock caverns (EPRI EM-1589, EM-2260), salt caverns (EM-2210), and aquifers (EM-2351). The storage of compressed air is, in many respects, identical to the underground storage of natural gas and oil. As Figure 1 shows, since 1915 the natural gas storage industry has operated more than 400 storage reservoirs in 26 states, with a total gas storage capacity of 7.7 trillion ft^3 (0.22 trillion m^3). Not shown on this map are about 1000 salt caverns and 70 mined caverns used for storing as much as 800 million barrels (126.8 million m^3) of liquid hydrocarbons, strategic petroleum reserves, liquefied petroleum gas, and gasoline. EPRI reviewed about 70 years' worth of site selection and development experience in the gas and oil industries and found it to be directly applicable to siting CAES plants (RP2488-10). Interested utilities were introduced to the details of CAES site development at an EPRI-sponsored geotechnology workshop in September 1986 and at three regional conferences (EM-4445).

Systematic procedures and a methodology for siting CAES plants are currently being developed (RP2488-8). The process of site identification, selection, and evaluation begins with a technical feasibility study and the optimal matching of underground storage and turbomachinery parameters. The pressure and temperature limitations of the air stored in a geologic formation dictate turbomachinery design parameters. A rock or salt cavern could be operated at constant pressure (by water or brine compensation) or as an uncompensated, constant-volume receptacle with variable pressure. Falling between these two types is an aquifer, whose porous nature and hydrodynamic characteristics make it partially pressure compensated.

The size of caverns and reservoirs (and hence the cost) is determined by pressure, temperature, and turboexpander air consumption for delivering rated power and energy during a generation cycle. The optimal matching of subsurface and turbomachinery parameters is generally based on the trade-off between the cavern costs and the energy (fuel and electricity) consumption costs. Cavern construction cost equations and parametric economic evaluation procedures have been developed (EM-3855). Figure 2 shows capital cost estimates for 25- to 220-MW CAES plants and three typical geologic formations for underground air storage; the analysis assumes a daily operating cycle with 10-h charging and 10-h discharging. The costs of underground storage in salt and aquifers are not very sensitive to plant size; however, the costs of rock caverns benefit from the economy of large-scale excavation.

Geologic siting criteria

On the basis of the CAES plant siting studies and the site methodology work, researchers evaluated a number of geotechnical parame-

Figure 1 Most of the 440 natural gas storage reservoirs in aquifers, depleted gas and oil fields, and excavated caverns in salt and rock formations are shown here. In addition, there are some 1000 salt caverns and 70 mined caverns for storing petroleum products (not shown). The long experience of the U.S. oil and gas storage industries is directly useful for siting CAES plants.

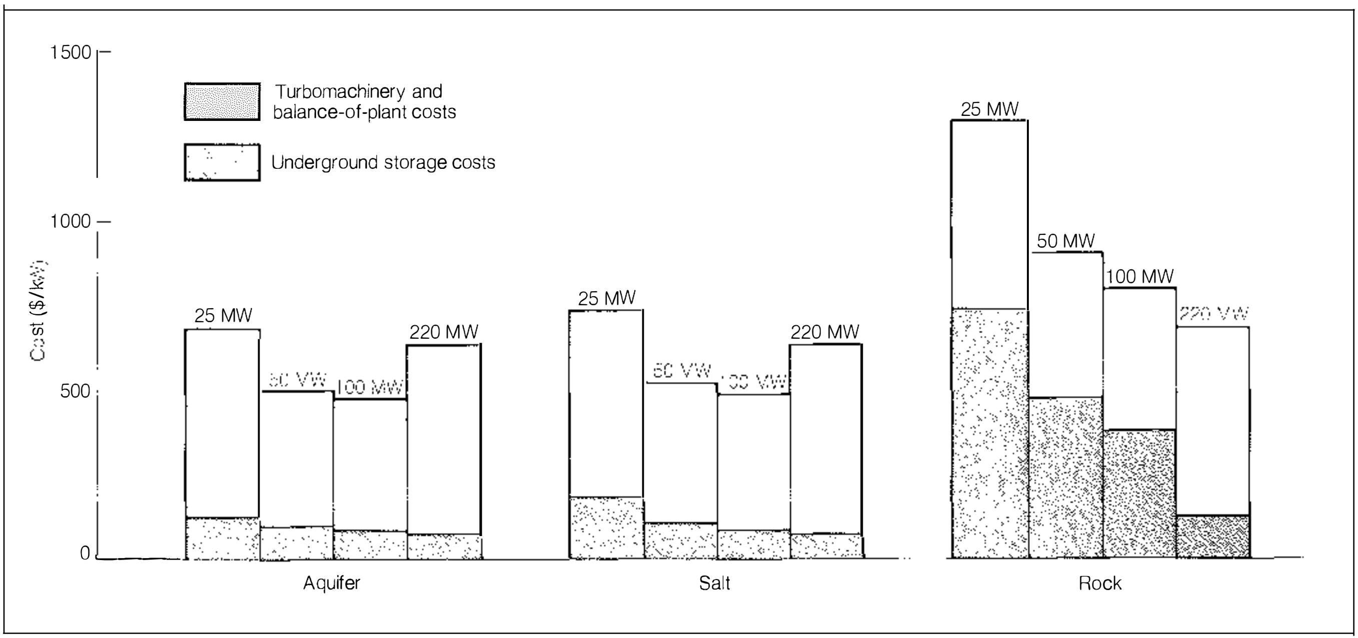


Figure 2 CAES capital cost estimates (in January 1987 dollars) are compared for four plant capacities and three typical underground storage formations. In each case the underground storage has a 10-h generation capacity. The estimates do not include interest during construction and land acquisition costs.

ters. The principal geotechnical criteria for rock caverns are rock mass strength, permeability, stability, depth, and thickness. In general, all igneous rock, most metamorphic rock, and some sedimentary rock have the required host-rock qualities. The structural integrity of the host-rock mass is determined by uniaxial compressive strength, frequency of detrimental discontinuities, and resistance to air-water deterioration. The ability to contain compressed air is measured by the rock's hydraulic conductivity. Fracture rechargeability and a shallow water table are also desirable for maximizing storage pressure while minimizing air leakage. The depth from the ground surface to the cavern roof governs the maximum allowable storage pressure, and the thickness of the rock formation controls the range for construction depth. Preliminary optimization work indicates that 100-ft-thick (30-m) rock formations with a compressive strength of 10,000–20,000 psi (69–138 MPa) and a conductivity of less than 2×10^{-6} cm/s at a depth of 1300–1900 ft (395–579 m) are desirable for rock caverns.

The major criteria for salt caverns are the depth from the ground surface to the top of the salt, formation thickness, and formation quality. Two types of salt formation are commonly used for cavern construction: bedded and domal. Salt formation is an evaporite sediment that is an accumulation of halite (NaCl) crystals precipitated from impounded sea water in an arid environment. Most salt deposits exist as layers of salt lying between beds of shale, anhydrite, gypsum, or limestone. Salt domes, however, are relatively narrow columns of salt that have been extruded upward from a massive bed at a great depth.

The depth from the ground surface to the salt cavern roof governs the maximum allowable storage pressure (equivalent to a lithostatic pressure of 1.0 psi/ft, or 22.6 kPa/m); the salt cover over the roof serves as an impermeable barrier to air leakage and gives structural strength to the cavern. For domal salt a maximum depth of 3000 ft (915 m) and a minimum 300-ft-thick (91.5-m) roof cover are recommended. Since bedded salt formations range in thickness from only 100 to 300 ft (30.5 to 91.5 m), the cavern depth is set by the top of the salt layer after allowing for an adequate salt roof cover. It is recommended that the salt cover over the storage cavern have a minimum salt content of 60% because insolubles, such as anhydrite (calcium sulfate), affect cavern stability and shape.

The important criteria for water- and gas-bearing porous-media sites are anticlinal structure, impermeable cap rock, appropriate depth, permeability, porosity, noncorrosive fluid, and mineral chemistry. These criteria are largely derived from the experience of the natural gas storage industry. If a site meets the requirements of structural integrity, fluid compatibility, deliverability, and storage volume, it should be sufficient for most CAES plant designs. These parameters from the Pittsfield, Illinois, CAES test facility are suggested as guidelines: 300-millidarcy minimum permeability, 100-ft minimum storage thickness, 15% minimum porosity, and 30% maximum water saturation.

Siting methodology

Defining the most suitable geotechnical conditions for a CAES plant site is fundamental. This information is necessary, first, for comparing various potentially suitable sites and, second, for achieving optimal integration and design. The following siting methodology has been outlined under RP2488-8.

- Site identification: assess local geology for CAES potential, determine CAES system requirements, define CAES study area, outline favorable geologic blocks, identify preferred sites within favorable blocks

- Site selection: rank potential sites for each geology, develop conceptual design and cost estimates for top-ranked sites, select optimal site

- Site evaluation: prove geotechnical feasibility of selected site

This approach is designed to rule out, as early and with as little expense as possible, flawed and environmentally constrained sites. When site choices have been narrowed to a manageable number, personnel should thoroughly investigate the suitability of the geotechnical conditions. The CAES site selection process also requires the evaluation of nongeotechnical factors.

Host utilities evaluated the methodology by applying it to specific examples. The following examples are typical of the three basic geologic formations and a hypothetical 100-MW CAES plant with a daily cycle of 10-h charging and 10-h discharging.

- Rock caverns: San Diego Gas & Electric Co. evaluated a virgin granitic rock formation near San Diego, California. Ohio Edison Co. evaluated an existing limestone mine in Barberton, Ohio, with an excavated volume of 300 million ft^3 (8.5 million m^3) at a depth of 2250 ft (686 m).

- Salt caverns: Houston Lighting & Power Co. evaluated a virgin site in the Big Creek salt dome near Houston, Texas. Mississippi Power & Light Co. evaluated two propane storage caverns in the Petal salt dome at Hattiesburg, Mississippi, each with a volume of 2.3 million barrels (0.36 million m^3) at a depth of 2700 ft (823 m).

- Porous media: Southern California Edison Co. evaluated aquifer sites and depleted gas/oil fields in the Los Angeles basin.

In each case site identification began with a broad classification of known geologic formations in the state. Most of the geologic data were obtained from state and local government agencies. These geologic areas were narrowed to a few desirable locations by applying nongeotechnical site-screening criteria, such as access to a transmission corridor, proximity to urban centers, and environmental regulations. Then screening and ranking criteria worksheets were prepared to evaluate the desirable locations. A number of concerns related to property acquisition and transportation logistics were considered in selecting the most preferred sites, and the risks and advantages of converting existing rock and salt caverns to CAES were evaluated. The host utilities reviewed these procedures for accuracy and ease of application. A brief checklist of the most important geotechnical and nongeotechnical factors was developed (Table 1). In each case the final site selection still requires coring, in situ testing, geophysical logging, and laboratory tests. The importance of the preconstruction and early site evaluation process cannot be overemphasized because case histories have shown that most major underground construction cost overruns result from belated discovery of adverse geologic features or from belated recognition of their significance.

Geotechnical research

Research is needed for developing and demonstrating methods that will help minimize the geotechnical risks and costs of siting subsurface energy storage facilities. A reluctance to proceed with such projects is particularly prominent in the case of technologies (like CAES) with which U.S. utilities have no experience. Some of the CAES research topics under investigation are the leakage and migration of stored air, oxygen depletion, and gas mixing.

Since 1973 nine Norwegian hydroelectric power plants have used closed, unlined rock caverns filled with compressed air instead of open, vertical surge shafts to dampen sudden pressure changes in the head race tunnel. With pressures up to 78 bars (7.8 MPa) and volumes up to 4.2 million ft^3 (120,000 m^3), these air cushions operate like constant-pressure CAES caverns. The loss of air due to leakage through the rock mass and dissolution in water is being measured to provide a reliable data base for designing airtight unlined rock caverns (RP2488-9). In other efforts researchers investigated some new mining methods and concepts for minimizing air leakage

Table 1
CHECKLIST FOR CAES SITING

Geotechnical Factors for Porous Media	Geotechnical Factors for Salt/Rock Caverns	Nongeotechnical Factors for All Media
Reservoir type	Formation	Land ownership
Geologic age	Salt/rock type	Mineral and storage rights
Type of geologic trap	Depth to top of rock/salt	Acquisition impediments
Storage-zone permeability, porosity, depth, thickness, extent	Formation thickness and extent	Land use and zoning
Discovery pressure	Rock permeability/salt quality	Proximity to urban population
Lithology	Cap rock type and thickness	Flooding and wind risks
Depth of crest	Rock quality designation	Subsidence and landslides
Formation-water analysis	Fracture frequency	Transportation logistics
Maximum storage capacity, working storage capacity	Proximity to faults	Nearest transmission substation
Proximity to faults	Seismic risk	Nearest power plant
Cap rock material, permeability, porosity, thickness, threshold pressure	In situ rock stresses	Fuel types and sources
Topography	Compressive and shear strength	Environmental regulations
Oil and gas production wells	Resistance to air/water	Permits and licenses
Observation and water wells	Geologic column log	
Core and log data	Topography	
	Groundwater table	
	Water source, quality, capacity	
	Fracture rechargeability	
	Aquifer data	
	Brine disposal method, capacity, license	
	Brine quality requirements	
	Existing oil/gas/brine well data	
	Core and log data	

(RP2488-6, -11). They estimated that the construction costs of uncompensated and compensated caverns for nominal 100- to 220-MW CAES plants with a 10-h daily generation capacity were comparable.

The Pittsfield aquifer tests demonstrated the feasibility of daily cycling of compressed air in an aquifer reservoir (*EPRI Journal,* April/May 1986, p. 52). An analysis of the data using natural gas reservoir engineering techniques confirmed that these methods could predict the flow pattern and deliverability of compressed air from porous storage media (RP2488-10). The results showed that there was no loss of oxygen when air was cycled daily. However, the oxygen content started to decrease from a nominal 21% during 12 months of a long shut-in period with no air cycling. Pertinent core and water samples were taken before, during, and after the Pittsfield aquifer tests in order to evaluate various oxygen depletion mechanisms (RP1791-15).

The most probable mechanism is postulated to be the oxidation of minerals, particularly iron sulfides, in the porous matrix at this site. The Pittsfield core analyses revealed the presence of pyrite in all three subunits of the St. Peter porous rock aquifer. The presence of this stable sulfide in reservoir waters of pH 7.5 suggests a geochemical environment that would be particularly sensitive to the presence of oxygen. Attacked by oxygenated groundwater, pyrite will oxidize to ferrous sulfate and sulfuric acid. The sulfuric acid, in turn, reacts with calcite, dolomite, and many complex clay minerals to release metallic cations that reprecipitate as sulfates, hydroxides, or oxides, depending on the availability of free oxygen and water. The posttest water analyses revealed a striking increase in the concentrations of calcium, iron, magnesium, manganese, zinc, and sulfate, which are also present in the accessory minerals. The presence of minerals, formation waters, and cyclic air pressure and temperature changes could cause oxygen depletion. The oxidation rate at Pittsfield was much lower than the daily air-cycling rate, as evidenced by the fact that significant oxygen depletion did not occur in the active air bubble during daily cycling. Further experiments are in progress to determine the reaction kinetics and screening criteria to evaluate other porous-media sites (RP8000-9).

Most natural gas storage projects are developed by using nearly depleted gas reservoirs because accurate geologic records are usually available from operators and regulatory agencies. There are approximately 25,000 producing or abandoned natural gas reservoirs of various sizes and performance characteristics in the lower 48 states. However, the use of such reservoirs for CAES introduces the potential problem of air-gas mixtures. In RP2488-10 researchers reviewed case histories of underground storage of propane-air mixtures in Michigan, helium storage in a Texas natural gas field, mixed-gas storage in France, and air-nitrogen injection for enhanced oil/gas recovery. They concluded from this preliminary analysis that compressed air or nitrogen could be used to sweep as much native natural gas as possible to prevent flammable mixtures in surface facilities. Also, they did not consider the presence of flammable mixtures underground to be a problem because the ignition temperature is over 1000°F (556°C) higher than the down-hole temperature. Even if an air-gas mixture was ignited, porous rock would act as a flame arrester, and the flame front would not be self-sustaining.

A field test program has been proposed by the Sacramento Municipal Utility District to develop an abandoned gas field in northern California for a 50-MW CAES plant for a seasonal storage cycle. Southern California Edison is evaluating several aquifers and depleted gas/oil fields to demonstrate the technical feasibility of building CAES plants in such porous media, and San Diego Gas & Electric is investigating a number of geothermal sites in the Imperial Valley of California (RP2615-1). The Italian national utility has recently started to inject air into a fractured-rock aquifer filled with carbon dioxide gas. The Dutch and Israeli electric utility research organizations are also evaluating aquifers for building CAES plants.

EPRI plans to help build the first U.S. CAES plant in each of the three basic geologic formations. Engineering specifications for the Alabama Electric Cooperative 50-MW CAES plant at the McIntosh salt dome site have been completed, and a geomechanical analysis is under way to validate the site's long-term stability (RP2615-2). The results of EPRI's continuing geotechnical research will help progressive utilities exploit underground storage space with minimal technical risks and environmental impact. *Project Manager: B. R. Mehta*

R&D Status Report
COAL COMBUSTION SYSTEMS DIVISION

Kurt Yeager, Vice President

IMPROVED COAL-FIRED POWER PLANTS

The coal fired power plant will remain the dominant source of electric energy in the United States through the year 2000 and beyond. Improved technologies for firing pulverized coal will be implemented, as well as advanced coal technologies like gasification and fluidized bed combustion. To provide better designs and materials for use in new and existing coal-fired plants, EPRI undertook a broad research effort in cooperation with U.S. utilities and international manufacturers and suppliers—the improved coal-fired power plant, or ICPP, project (RP1403).

There are more than 1200 fossil fuel power generating units in the United States. One goal of the ICPP project and related EPRI research is to demonstrate the technology necessary to improve the heat rate of existing U.S. plants by 3% and their availability by at least 5%. The project also seeks to demonstrate the technology required for specifying new pulverized-coal-fired plants capable of operating in a cycling mode with improved availability. These plants will have a low-load capability down to 15% and will offer heat rates up to 14% better than those of current plants with steam conditions of 2400 psig (16.5 MPa) and 1000°F (538°C).

Fluidized-bed technology and integrated gasification–combined-cycle plants, whose development is being spearheaded by other EPRI projects, will assume a growing role in coal-fired generation. As these technologies mature and are proved in utility service, materials and designs from the ICPP project will be available to improve their reliability, availability, and heat rate.

The ICPP project, then, is aimed at meeting the immediate and future generation needs of utilities in the United States. Making international technology available to U.S. utilities is a cornerstone of the project, and EPRI has formed research consortia—led by U.S. companies—of major equipment manufacturers, suppliers, and architect/engineers worldwide. Project participants, including the host utilities, also support the research through cofunding, which makes up approximately 35–40% of the total funding. The research teams are as follows.

- Turbine: General Electric, Toshiba, Alsthom, M.A.N.
- Boiler: Combustion Engineering, Mitsubishi Heavy Industries, Sulzer Brothers, Foster Wheeler Development Corp., Ishikawajima-Harima Heavy Industries, Bailey of Japan
- Balance of plant: Brown Boveri, Sulzer Brothers, Pump Research and Development Co., Foster Wheeler Development Corp., ENCOR America, Heat Exchanger Systems, Bailey Controls, Bailey of Japan, Kyushu Denki Seizo
- Retrofit: Gilbert/Commonwealth, Stone & Webster Engineering Corp., Westinghouse Electric Corp., Hamon-Sobelco, Burns and Roe, Babcock & Wilcox Co., Combustion Engineering

Upgrading existing plants: availability, cycling, heat rate

For many aging units, life extension is the economic choice, and upgrading their efficiency often leads to increased unit capacity. New materials and components can afford longer service life, improved reliability and availability, and increased cycling capability. Among the advantages of better materials are improved strength and erosion resistance.

Several innovations are already available for retrofitting and upgrading existing plants. Figure 1 illustrates the improvement in service life at given design stress levels with a new alloy called super 9Cr steel. This alloy's improved strength also makes possible the use of thinner heavy-section parts, which vastly improves loading rates and unit restart times. New component designs to improve cycling capability are available as well—for example, the header

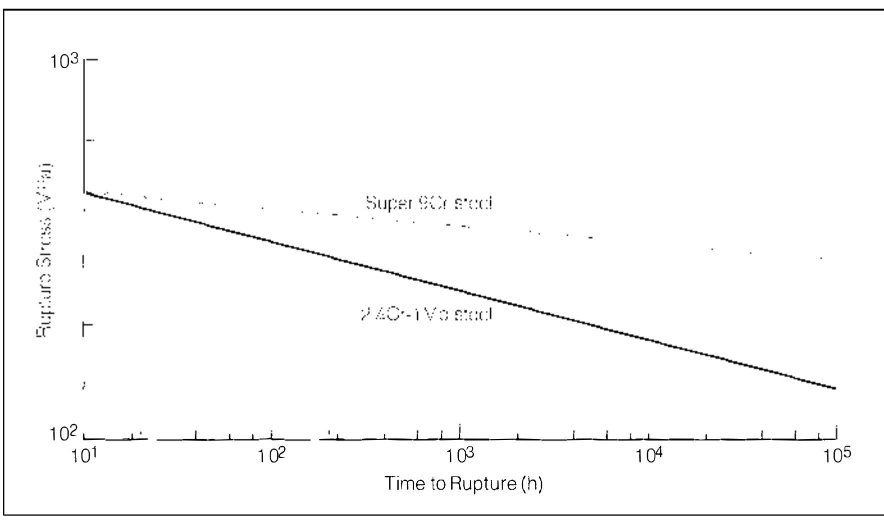


Figure 1 Super 9Cr steel has demonstrated greater strength than conventional 2¼Cr-1Mo steel, which translates into longer service life for power plant components. These data are from constant-temperature (900°F; 482°C) tests.

feedwater heater, which eliminates the heavy tubesheet and thus the tube-tubesheet connection.

Significant availability benefits for existing plants can result from the use of improved boiler and turbine materials. Despite the generally higher cost of materials with greater resistance to creep and corrosion, the availability savings easily exceed the initial investment. The following are typical material enhancements that can be applied to utility boilers and turbines.

- Superheater/reheater tubing with high-chromium cladding to prevent coal ash corrosion
- Superheater/reheater tubing with internal chromizing or chromating to mitigate exfoliation, which leads to turbine and valve erosion
- Rifled waterwall tubing of wrought super 9Cr steel to prevent "alligator" cracking failures
- Cast valve bodies and wrought piping of super 9Cr steel for longer creep life under cycling duty
- High- and intermediate-pressure turbine rotors of improved 12Cr steel for longer creep life under cycling duty
- Low-pressure (LP) turbine rotors of ultra-clean NiCrMoV steel for resistance to temper embrittlement

These improved materials will also enhance a plant's cycling capability. The stronger ferritic materials, for instance, permit the use of much thinner parts than conventional steels do—without sacrificing thermal conductivity.

Plant control and safety systems are antiquated in many existing plants. The microprocessor-based distributed digital control systems that are being validated for new cycling plants will provide many spin-offs for older plants. For example, adaptive digital control systems, which will be studied as part of the ICPP project, can be retrofitted to existing systems for improved startup and steam temperature control.

Feedpumps and high-pressure feedwater heaters continue to be a concern for existing units in terms of availability and cycling. Improved designs for tubesheet and header feedwater heaters for cycling service will be investigated, and selected designs will be validated in service in existing fossil fuel plants.

Recent advances in waste heat recovery and equipment modification can improve the heat rate of existing plants. The following utility demonstrations are planned.

- Conversion to full sliding-pressure operation of a supercritical coal-fired plant designed for fixed-pressure operation
- Recovery of waste heat from flue gas through a heat pipe heat exchanger
- Use of a corrosion-resistant low-level heat exchanger to recover flue gas waste heat
- Recovery of energy from circulating water
- Installation of low-excess-air burners with an improved damper control system

Efforts in three of these areas, sliding-pressure operation, heat recovery from circulating water, and heat pipe heat exchangers, are under way with Burns and Roe, Stone & Webster, and Babcock & Wilcox, respectively. Initial results will be available in late 1987 and early 1988. Work is expected to begin in the next year on corrosion-resistant low-level heat exchangers. Several additional heat rate improvement projects are under consideration.

Boiler materials R&D

Superheater corrosion caused by liquid sulfates has plagued the industry since the 1950s, when the use of high-sulfur coals increased. R&D by EPRI and others has shown that the following factors contribute to the severity of liquid ash corrosion: the amount of liquid sulfate deposited on the tube, the sulfur content of the coal, the chlorine content of the coal, the temperature of the tube, and the chemical composition of the alloy.

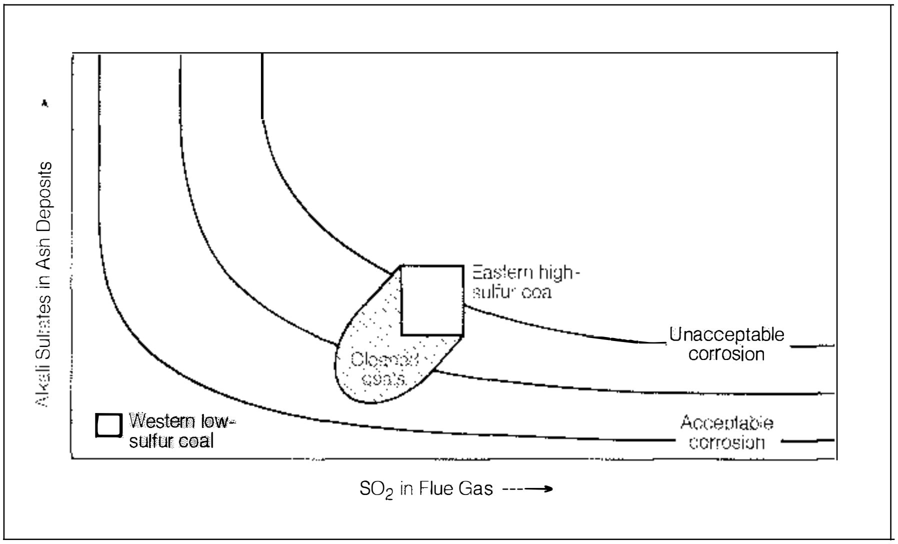
Although the effects of these factors are broadly understood, it has been difficult to predict the corrosivity of a given coal from its chemical composition and ash properties. The main unknown has been the amount of liquid sulfates that will be deposited on the tubes. The composition and quantity of the liquid sulfates that will form cannot be predicted from the coal characteristics because not all of the sodium, potassium, and iron present in the mineral matter of the coal is available to form sulfates; potassium, for example, is largely associated with silicates. Therefore previous attempts to relate the corrosivity of coals to the amount of water soluble or acid-soluble alkali they contain have been only partially successful in predicting metal loss.

The approach adopted in RP1403 consists of determining, in the laboratory, the corrosion loss of various candidate alloys as a function of the alkali sulfates in the coal ash deposits, the sulfur dioxide (SO_2) content of the combustion gas, and the temperature. This work will be complemented by laboratory combustion tests and by field tests of probes and loops in operating boilers. The combustion tests will yield information for correlating coal properties with the formation of alkali sulfates, and the field tests will validate the overall approach. Cooperating utilities include Philadelphia Electric Co. and the Tennessee Valley Authority.

Isocorrosion diagrams are developed for each test material on the basis of the laboratory data; Figure 2 presents an example. Such diagrams could potentially be used to evaluate materials and coal-cleaning strategies. The correlation between laboratory data and field data is tenuous at present, however, because of the lack of good field data. The field tests under RP1403 will remedy this problem.

In the meantime, isocorrosion diagrams provide a basis for ranking the corrosion resistance of various alloys. The results for the 17

Figure 2 Corrosion weight loss as a function of the alkali sulfates in coal ash deposits and the SO_2 in flue gas (at constant temperature) is shown for a superheater material examined in RP1403. (Weight loss is constant along a given curve.) Also indicated are the conditions expected in service with typical coals and the potential benefits of coal cleaning. Work is under way to quantify the relationships shown conceptually here.



materials and 4 coatings tested to date under RP1403 will be published as a guide for that purpose. And as more data become available, the information will be updated to provide a quantitative link between coal properties, alloy composition, and field corrosion rate. The success of this effort will enable utilities to make accurate boiler life predictions on the basis of data from laboratory tests, which are much less costly and more quickly performed than field probe tests.

Ultraclean LP rotor steel

Over the past 10–15 years, the art of steel making has become so advanced that many of the impurities resulting in degraded properties or impaired service performance can be eliminated by refining or processing techniques. Concurrently, basic research on the mechanisms by which steel is embrittled has identified the kinds and amounts of impurities that result in degraded properties.

From 1975 to 1983 EPRI supported studies on laboratory-made high-purity steels by the University of Pennsylvania (RP559-1), Japan Steel Works (RP2060-1), and Bethlehem Steel Corp. (RP2060-2). This work demonstrated that temper embrittlement in the low-alloy steels used in utility components can be virtually eliminated by reducing manganese and silicon to low levels (0.02–0.05%) while maintaining sulfur, phosphorus, tin, arsenic, and antimony at levels of 10–30 ppm. (Hydrogen was maintained at 1 ppm, oxygen at 25 ppm, and nitrogen at 50 ppm maximum in these investigations.) Such steels not only were resistant to temper embrittlement but also were tough, strong, and ductile, with unimpaired creep strength in comparison with steels of conventional purity.

The operating temperature of an LP turbine made of conventional 3.5NiCrMoV steel is limited to about 600°F (315°C) maximum in order to avoid temper embrittlement during service. Keeping the LP turbine at or below this temperature requires the use of cooling steam, which impairs a plant's heat rate. Under RP1403-8 EPRI set out to determine whether the high-purity LP rotor steel already demonstrated in the laboratory could be produced at modern ladle refining and vacuum degassing facilities. A model rotor was fabricated at the Vereinigte Edelstahlwerke (VEW) shop in Kapfenberg, Austria.

Extensive evaluation of this model rotor by VEW and many outside organizations confirmed that it was completely resistant to temper embrittlement after 10,000 hours of aging over the susceptible range of 700–1000°F (371–538°C); also, it was found to be superior to conventional 3.5NiCrMoV steel in terms of fracture toughness and tensile ductility over a yield strength range of 100–130 ksi (689–896 MPa). One shortcoming was a variation in yield strength from the center to the perimeter. This problem was overcome in a subsequent model rotor forging produced for Toshiba by Japan Steel Works with improved heat treatment. EPRI is now sponsoring the evaluation of this rotor by an international panel of experts under the ICPP program.

On the basis of the successful laboratory and trial rotor experience, Toshiba has made two production-size rotor forgings of the ultraclean 3.5NiCrMoV steel for a 700-MW Japanese unit firing liquid natural gas and featuring steam conditions of 4500 psi (31 MPa) and 1050/1050/1050°F (565°C). The selection of the EPRI ultraclean NiCrMoV rotor steel marks a significant advance for the utility industry.

EPRI is actively seeking to apply this steel at U.S. utilities either in new units or in replacements for old, temper-embrittled LP rotors. For existing lower-temperature (900°F; 482°C) plants or cogeneration plants, the steel represents a tougher alternative to conventional 3.5NiCrMoV for high- and intermediate-pressure rotors as well as LP rotors.

Super 9% chromium steel

Many existing pulverized-coal-fired plants, and virtually all future improved plants, will be required to cycle. The frequent startups and load changes this involves can result in high temperature differentials and thermal stresses across heavy-section components like turbine casings, steam chests, nozzle blocks, main steam piping, and valve bodies. Ferritic or martensitic 9–12Cr steels have a clear advantage over austenitic steels for these applications because of their higher thermal conductivity and lower thermal expansion coefficients. Also, 9Cr steels have potential for casting, and the use of casting instead of forging for large, complexly shaped components would afford economic and technical advantages.

In a review of 9–12Cr alloys for RP1403, a modified 9Cr-1Mo (91 grade) alloy developed by Oak Ridge National Laboratory and Combustion Engineering was selected for evaluation in heavy-section cast components. This alloy, known as super 9Cr steel, is comparable in creep strength to austenitic stainless steels and has the desirable thermal characteristics of ferritic steels. There are extensive data on super 9Cr in wrought form because it has been qualified for the ASTM Boiler and Pressure Vessel Code; there are few data on super 9Cr castings, however, and they have not yet been approved for the code.

Under RP1403 the European turbine contractors Alsthom and M.A.N. have selected a composition for the cast version, have made production-size castings, and are developing a data base for code qualification of castings. The initial work, performed by the George Fischer foundry in Schaffhausen, Switzerland, confirmed the finding of earlier work done in Japan by Ishikawajima-Harima Heavy Industries: that the wrought composition range also was optimal for castings. George Fischer has cast large test blocks and simulated valve bodies of super 9Cr steel, and similar castings will be made by foundries in the United States and Japan. Detailed evaluation of the mechanical properties of these castings will provide data for the ASME Code case. Also, work is in progress at Combustion Engineering on the bending and welding of super 9Cr.

Improved technology for new plants

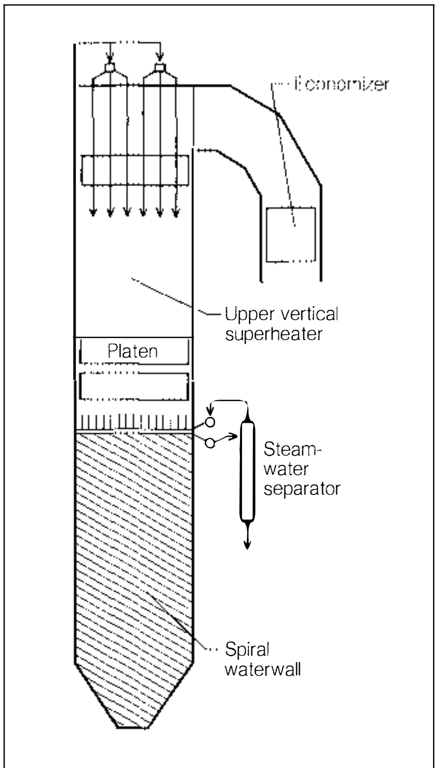
RP1403 will provide design and materials technology for new cycling plants in the 200–700-MW size range. Design work is under way for two plant sizes (700 MW and 350 MW). Additional work will follow to extend these designs to plants 200 MW and smaller.

Boilers There are major concerns about constant-pressure operation of the boiler in a cycling plant. Power consumption in the boiler feedwater pumps and at the turbine throttle reduces unit efficiency. During startup and operation, when the boiler valves are throttling the flow, cavitation damage may lead to availability loss. Finally, and most important, in the constant-pressure mode load changes may cause large temperature changes in the first stage of the high-pressure turbine.

EPRI studies have considered these concerns and have concluded that variable-pressure operation of the steam generator will be required for future cycling coal-fired power plants. For supercritical units this operating mode requires a once-through boiler, in which the fluid passes through the waterwalls only once (i.e., there is no recirculation as there is in a drum boiler). For subcritical units variable-pressure operation is possible for both drum and once-through boilers.

Waterwall geometry is another design issue for variable-pressure cycling boilers. In vertical-waterwall boilers, the tubes are arranged vertically; in spiral-wound boilers, they spiral around the furnace. Because of their slope, fewer spiral tubes are needed for the same wall area, which increases flow per tube and prevents departure from nucleate boiling. Since the fluid "sees" all the furnace walls, temperature differences around the furnace are averaged out, resulting in greater steam temperature uniformity. These advantages are more important at part load than full load—for all boilers but especially for small ones.

Figure 3 This spiral-wound-waterwall boiler integrates heat flux for all circuits and reduces the number of circuits for a given plan area. As a result, the design allows full cycling capability for boilers below 700 MW in size.



Both vertical-wall and spiral-wound boilers are included in the EPRI project—the common denominators being fuel flexibility and the ability to cycle. Preliminary design work is already complete for 700-MW vertical-wall and 350-MW spiral-wound supercritical boilers. It is anticipated that for supercritical variable-pressure boilers, the vertical-wall design will have a lower size limit somewhat less than 700 MW. Below this limit, the spiral-wound design must be employed. The converse is not true, however; the spiral-wound design may be used for plants 700 MW and larger, although its more complicated fabrication procedures and more elaborate support structure may impose economic penalties.

The spiral-wound boiler design addresses cycling operation in the size range most likely to be considered for the next generation of U.S. plants. Two arrangements have been evaluated. In one, the steam-water separator lies between the spiral waterwalls and a vertical superheater section (Figure 3). Although simple mechanically, this alternative requires a higher-strength alloy, such as super 9Cr, for the waterwalls. In the other arrangement, a vertical radiant wall superheater lies immediately above the spiral waterwalls. This alternative uses standard carbon steel (SA-213 T11) in all sections of the waterwalls but involves a more complicated mechanical design.

The vertical-wall boiler design incorporates rifled waterwall tubing to avoid film boiling in the subcritical mode and pseudo-film boiling in the supercritical mode. These waterwalls will benefit from the use of super 9Cr alloy.

Turbines Cycling capability is also the focus of the turbine R&D program. The cycling capability of a supercritical turbine is defined in terms of the time required to place the unit on-line after various shutdown periods and the ability to follow load changes while in service.

Current U.S. supercritical units cannot be used for two-shift duty (on-off cycling) because of their lengthy startup times. Also, in general, their minimum load is limited to 30% of rated load because of steam generator or control system constraints. The situation is different in Europe and Japan, where supercriticals are often two-shifted and achieve low loads of 15–20%. These units and their startup systems were designed for cycling and mid-range duty—in contrast to the U.S. units, which were designed originally for baseload.

EPRI studies have determined that the next generation of U.S. supercritical units should be capable of cycling with a minimum loss of material and component life. For the turbine this implies a design that can routinely start from a cold condition within 12 hours, from a warm condition within 4 hours, and from a hot condition within 2 hours. The cumulative cyclic life expenditure associated with this duty should allow a normal life of 30 years, with no loss of reliability or availability in comparison with subcritical drum units.

For steam turbines, shells and rotors are the major cycling concerns. Calculating the cyclic stresses at the limiting locations yields the specific life expenditure for a given transient. Such curves can be used to control startups and load change rates in conjunction with an on-line computer that monitors temperature at critical locations.

Under RP1403 preliminary design work is complete for a 700-MW cycling turbine and is under way for a 350-MW cycling turbine. Future efforts will extend these designs to 200 MW and below. An important conclusion from the work to date is that the turbines can be built entirely from ferritic materials for steam conditions up to 1100°F (593°C) and 4500 psi (31 MPa). Such turbines easily satisfy the starting and loading times noted above. *Project Manager: George Touchton*

R&D Status Report
ELECTRICAL SYSTEMS DIVISION

Narain G. Hingorani, Vice President

PLANT ELECTRICAL SYSTEMS AND EQUIPMENT

Nondestructive evaluation of generator retaining rings

Most modern electric generators employ a nonmagnetic retaining ring at each end of the rotor to contain the end windings of the machine. Many generators in service today have rings made of an 18Mn-5Cr cold-expanded alloy. The strength and fracture toughness of this alloy make it well suited for this purpose. Unfortunately, the alloy is also highly susceptible to stress corrosion cracking in the presence of moisture or other contaminants.

Stress corrosion crack growth can be rapid if the unit is exposed to moisture from leaks or condensation. As little time as 1000 hours may be sufficient for a crack to propagate to failure under these conditions. The use of fracture mechanics techniques to establish inspection intervals is complicated by this high crack growth rate. Consequently, in-service examination methods are needed to detect cracks while they are very small to ensure that they do not grow to critical size before the next inspection cycle.

In RP2719-1 EPRI sponsored a worldwide investigation of nondestructive evaluation (NDE) practices for generator retaining rings (*EPRI Journal,* November 1985, p. 54). The objective was to develop recommendations for possible research projects to improve and qualify examination techniques and make them available to U.S. utilities.

From a utility standpoint, it is desirable to examine retaining rings while they are shrunk onto the rotor. The ultrasonic techniques used to detect cracks throughout the shrunk-on ring have to be perfected to permit unambiguous interpretation of the ultrasound indications. The nature of the ring material, ring geometry, and ring installation may result in the detection of false signals or signals from harmless defects, which cannot always be distinguished from crack indications. Worldwide opinion on the reliability of ultrasonic examination methods is sharply divided, and the practices for retaining ring ultrasonic examination are far from uniform.

To furnish utilities with an independent assessment of inspection methods for shrunk-on retaining rings, researchers at EPRI's NDE Center in Charlotte, North Carolina, have been examining several rings provided by utilities. Most of these rings were retired because they were subjected to stress corrosion environments and showed evidence of cracks at various locations. The rings are shrunk onto special mandrels to simulate the actual utility situation (Figure 1). The mandrel geometry duplicates the rotor body in the most critical area of the shrink fit. The amount of interference is identical to that in the original rotor design.

The rings are to be used for validating the inspection offered by various organizations. Utilities, original equipment manufacturers, and inspection service vendors can bring their equipment and personnel to the NDE Center to verify the capability of their detection methods.

In future work at the center, researchers will investigate the use of traditional NDE techniques, such as eddy-current and liquid-penetrant tests, and possible improvements to these techniques. They will also evaluate existing automated or semiautomated methods developed by EPRI for use in nuclear power plants.

To inform member utilities of the latest devel-

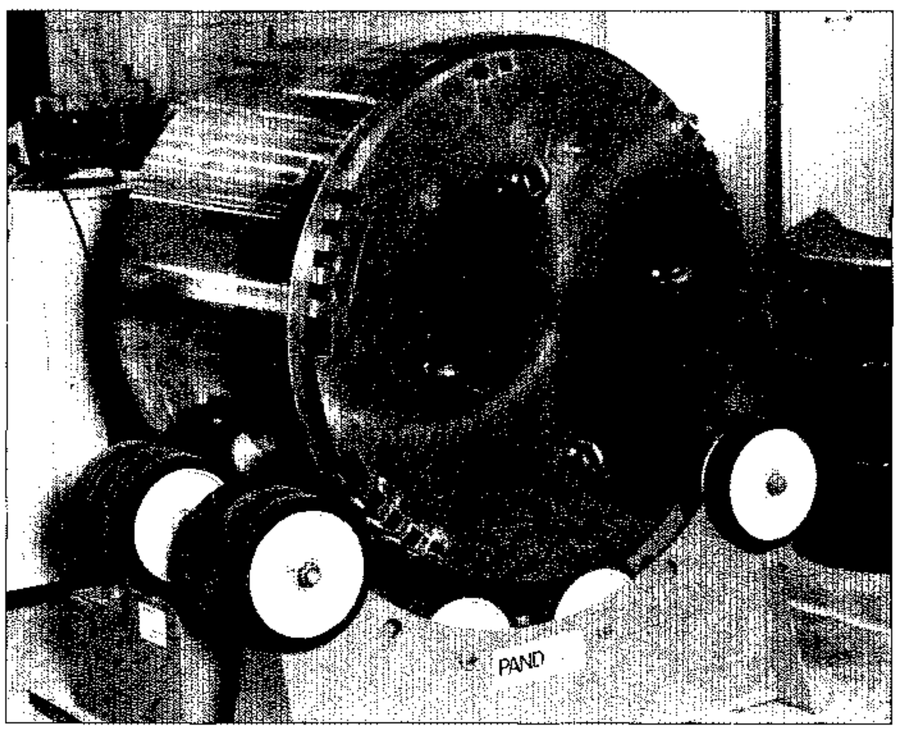


Figure 1 This shrunk-on generator retaining ring is being used in verifying ultrasonic inspection techniques at EPRI's NDE Center. The mandrel geometry duplicates the generator rotor body in the shrink-fit area.

opments in retaining ring inspection techniques, a three-day workshop will be held September 15–17, 1987, at the NDE Center. Also, a special EPRI report that presents inspection guidelines is available (EL/EM-5117-SR). Although general in nature, these guidelines will help personnel working in the area of stress corrosion of generator retaining rings to become familiar with the multidisciplinary issues involved in inspection and with the tools and methodologies currently available. The report presents useful information on retaining ring function, design, and stresses and includes a condensed chapter on fracture mechanics and material properties for magnetic and nonmagnetic rings. It also discusses an alternative ring material that is less susceptible to stress corrosion. *Project Manager: Jan Stein*

Improved temperature sensors for large rotating machines

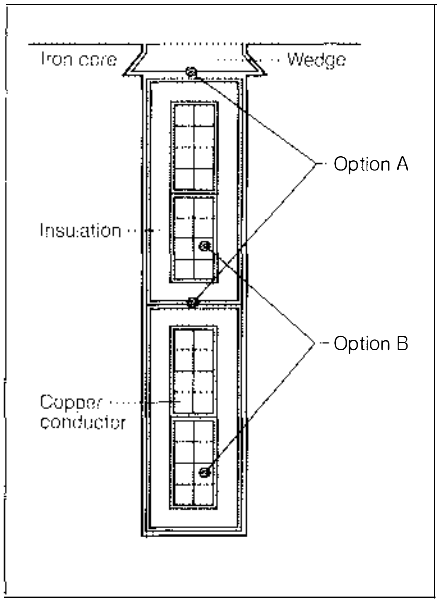
Temperature measurements of stator windings in large electric generators and motors have always been of interest to operating utilities. Several types of localized temperature sensors, such as resistance temperature devices (RTDs) and thermocouples, are used.

The data interpretation obtained from these temperature sensors is usually limited to recognizing a trend and taking action before serious damage occurs. There are, however, several failure mechanisms that can cause extensive damage within minutes if not detected quickly and reliably. Examples of such potentially damaging, rapidly progressing failures are coil internal short circuit and localized loss of coolant. Any excessive heat generated within the coil can destroy the groundwall insulation. Electrical shorts within the copper winding itself, such as turn-to-turn and strand-to-strand shorts, cause overheating, copper melting, shorts to ground, core damage, and other problems. Complete blockage of hollow strands in a single bar, causing extensive winding damage, has been reported, even though the machine was equipped with thermocouples at each water outlet.

Two EPRI projects are intended to improve existing temperature technology by providing early warning of damage (by using direct copper contacts) and to monitor each winding component, such as coils, rings, and leads (RP2308-6, RP2487-1). Distributed temperature sensing, now available with the advent of fiber optics, can greatly improve temperature measurement capabilities.

The feasibility of such distributed temperature sensors was the subject of the Battelle, Columbus Laboratories investigation, and a generalized concept of employing the distributed sensor in each generator bar was developed (RP2308-6). In addition, several thermo-

Figure 2 Generator stator slot cross section showing typical high-voltage coils and placement of the fiber-optic temperature sensor. Option A demonstrates the concept suitable for existing windings. In option B the sensor is in direct contact with the current-carrying conductor.



sensitive materials were identified. A joint effort by Battelle and Corning Glass Works is currently under way to produce a demonstration model of a true distributed fiber-optic sensor. A true distributed temperature sensor is one that not only has the sensing capability but also defines the location and length of the sensing region.

Figure 2 shows an axial cross section of a generator slot. In a concept introduced by Ontario Hydro, the fiber sensor is placed under the slot wedge and/or in between the top and bottom winding bars (option A). This application is particularly suitable as a retrofit for generators that need rewedging. Most of the optical fibers are mechanically strong and could be installed under all wedges during a rewedging job.

Option B in Figure 2 is a concept developed by Westinghouse (RP2487-1). This system, suitable for new windings, places the sensor inside the high-voltage (and thermal) insulation in direct contact with the conductors. The work done by Westinghouse will provide approaches and solutions to many of the practical problems that have to be resolved before instrumenting the generator with the fiber-optic sensors.

The inherent advantages of distributed temperature sensing over traditional point sensors extend the potential applications beyond monitoring stator coil temperature. Series and parallel winding connections, leads, and terminal connections can be included in the monitoring system. The stator core temperature monitoring can extend to larger areas of interest, such as end zones, the slot bottom, and the dovetail attachment. The ability to locate hot spots in the rotor winding may become a reality once a rotating optical coupler is developed.

Other applications for distributed sensors are in real-time thermal monitoring of overhead line conductors, establishing the temperature rise in feeder cables during a fault condition, and measuring tray cable temperatures. *Project Manager: Jan Stein*

Rotor-mounted monitoring system for hydrogenerators

The objective of this project is to develop a relatively simple, effective, and inexpensive device for monitoring the stator from the vantage point of the rotor, a device that would sweep over the entire stator on a continuous basis, once each revolution (RP2591-5). The design, component evaluation, fabrication, and bench testing of such a monitor have been completed. Next the components will be thoroughly inspected for any signs of deterioration. All the electronic modules passing the quality control tests will be installed in a special sensor bridge that will be mounted between adjacent pole pieces on a hydrogenerator rotor for field testing.

Once each revolution the sensors will provide data on temperature distribution, partial discharge activity, and acoustic noise at each coil, locating any distress in the stator precisely (i.e., by the slot). Infrared detectors mounted in the sensor bridge monitor temperature distribution. The signals from all sensors are processed electronically, converted to light signals, and transferred to optical receptors mounted on the stator, where they are fed to a minicomputer for final processing and display.

The Bonneville Power Administration has agreed to cofund and participate in the field installation and operational testing of the monitor. Some of the field tests have been designed to produce various data profiles of the stator. These temperature, acoustic, and radio-frequency signal (from the presence of arcing) profiles will be made at various voltage and load levels. The machine chosen for the field tests has known problems. Project personnel will use the data collected by the monitor to determine the extent of repairs needed on the generator.

The basic concept of the monitor could apply equally well to turbine generators. The principal barrier to be overcome is finding a suitable place on the rotor to mount the sensors. *Project Manager: James Edmonds*

TRANSMISSION SUBSTATIONS

Substation digital control and protection systems

At present, sets of stand-alone systems or devices control a typical transmission substation. Although this scheme is a perfectly acceptable one, it is unnecessarily costly and redundant because it duplicates wiring and functions. A digital system that meets all control and protection requirements should help the industry significantly reduce cost per function. EPRI and Public Service Electric & Gas Co. (PSE&G) are developing such a system for transmission substation applications. The research strategy is to develop a whole system instead of individual stand-alone units for each function. The goal is to reduce costs and improve system performance with a distributed, microprocessor-based system. The microprocessor is a small, relatively inexpensive component that could make the system modular and therefore expandable and easily maintainable.

The main technical challenge is to develop a system architecture that balances cost, performance, and substation topology, which is a major problem for system architects. To simplify system design, researchers made one basic assumption: The control and protection system would be hierarchical. It would incorporate a computer that would act as system master. With this assumption in mind, they established the following performance criteria.

- The critical protective relays must operate even if the substation computer fails.
- With sufficient redundancy, the system will perform all critical processing even if a single component fails anywhere in the system.
- The system must not require more than one completely redundant data acquisition unit to satisfy the above criteria.

The single-component failure criterion can be realistically met by permitting only a full set of redundant protective relay processors and data acquisition units; the selected architecture permits this and also meets the last criterion, which limits the number of data acquisition units that can be used to satisfy the single-failure criterion. The last criterion was introduced to ensure an economically viable system.

After careful analysis of the system requirements, developers selected a system architecture. At the first level are those functions common to the whole substation, and the substation operator can communicate with the entire system. Level 2 contains all critical processing, which includes all the protective-relaying functions. Level 3 is the interface with the power system. At this level, data are digitized for transmission to the protective-relaying processors, and control commands from the system control center and levels 1 and 2 are converted to output that operates the power equipment (e.g., breakers and switches).

The project covered the installation of a prototype system for the control and protection of one substation and the installation of matching devices for the protection of one line terminating in the station. The substation selected for the system demonstration is PSE&G's Deans substation; the protected line connects the Branchburg substation.

The Deans system, built by Westinghouse Electric Corp., has a station computer (SC), three protection clusters (PCs), one each for line, bus, and transformer protection arranged to separate protection zones, and five data acquisition units (DAUs). A second line protection unit of different design, to be built by General Electric Co., which incorporates two DAUs, is also part of the system. Each of the DAUs is connected to one or more PCs. Two of the DAUs, one supplied by General Electric and one by Westinghouse, are located in the switchyard and transmit signals by fiber-optic cables. The rest of the equipment is located inside the control house. The General Electric modules are being delivered in 1987.

Two digital terminals protect designated transmission lines and communicate with each other over a power-line-carrier channel. The two Branchburg terminals employ almost the same basic hardware and software modules as the Deans units. The Branchburg equipment stands alone and interfaces with other substation equipment, but a utility can easily modify the system to communicate with control, relay setting, and other terminals from a remote location.

The Deans system was installed in August 1986 and is now operating in the substation with simulated input. The substation input equipment will be connected after a short test to verify that the system performs well in the substation environment. Output connection for control of the substation equipment will be delayed until the system is fully debugged. A demonstration of the system was given to the Transmission Substation Task Force members on September 9, 1986 (Figure 3).

The Branchburg relay units have been installed since late 1984 and are in an open-loop (without output connected to the substation equipment) test operation. *Project Manager: Stig Nilsson*

Gas-in-oil monitor

EPRI has developed an on-line, low-cost gas-in-oil monitor that eliminates the need for periodic gas analysis of transformer oil (RP2445). Dissolved gases in transformer oil that are generated by arcing, corona, local overheating, and/or paper or oil insulation deterioration are vital signs of incipient faults. Gas-in-oil analysis has therefore become a valuable part of maintenance programs for preventing catastrophic failures. It is costly to perform periodic oil sampling and laboratory analysis of the extracted gases, however, and valuable time for identifying transformer problems can be lost in the process.

The Westinghouse Electric metal oxide sen-

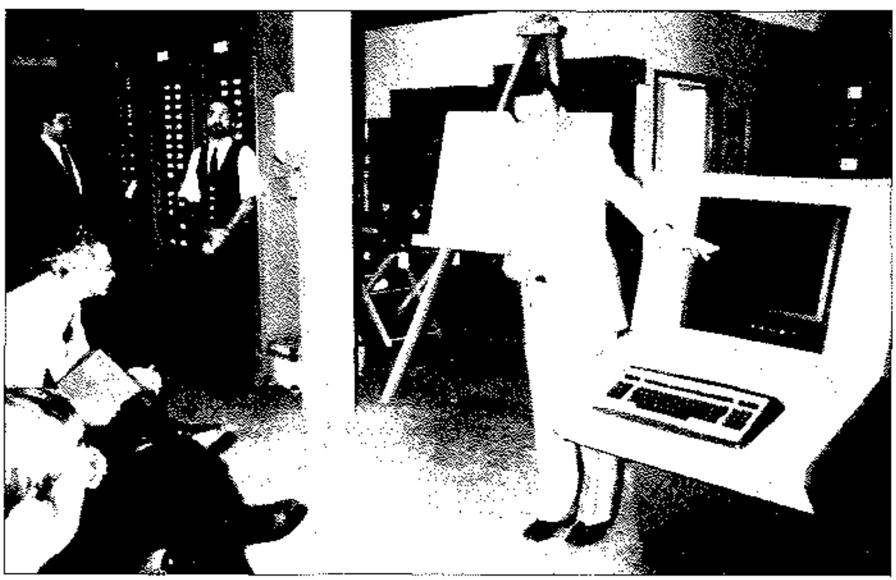


Figure 3 Demonstration of a new digital control and protection system for transmission substations.

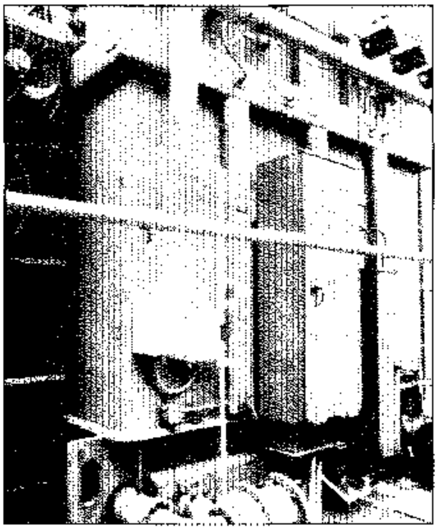


Figure 4 Gas-in-oil monitor installed on a transformer. The thermosiphon is at the top; the sensor cabinet is below it on the left; and the control cabinet is to the right.

sor (WEMOS) is designed to provide frequent and accurate analytic information on transformer gassing (Figure 4). It continuously extracts gases from the transformer oil and analyzes a portion of the collected gases once every 12 hours.

WEMOS provides timely information on the cause and progress of faults because it is sensitive to two key gases (individually), hydrogen and carbon monoxide. If predetermined levels of these combustible gases are present, the monitor initiates an alarm. Best of all, the cost of continuous monitoring with the instrument is sufficiently low to allow its use on large power transformers—and possibly on medium and small transformers as well. *Project Manager: Selwyn Wright*

Advanced thyristor valve

In October 1985 a field prototype valve developed under RP1291-5 was energized at the Sylmar converter station of the Pacific Intertie. Because the valve is rated at 133 kV and 2160 A, it could directly replace a 1970-vintage mercury arc valve. The Los Angeles Dept. of Water & Power is conducting the field tests.

The valve's novel features include higher-voltage thyristors with light triggering, a cesium vapor flash lamp as a light source, and a two-phase cooling system using refrigerant 113.

Because Sylmar is an important station that was already commissioned when the trial began, only a brief time during the annual maintenance period was available for the final installation and checkout of the valve. Over the first few months of the trial, several brief outages occurred as a result of items that would normally have been settled during a commissioning period. These were followed by two outages of a more serious nature.

In the first, nylon 11 hoses were found to be embrittled by the refrigerant they carried and were replaced by Tefzel. In the second, it was discovered that the malfunction of a refrigerant-level sensor allowed a resistor to overheat so much that the refrigerant could be decomposed. The cooling system was flushed clean, and two sensors were installed in place of the failed one.

At that time, personnel noted during a check that the ends of the optical fibers near the cesium lamp were degrading. An inch of damaged length was removed from each, and a UV filter was installed to prevent recurrence of this problem. The valve was reenergized on September 13, 1986, and has worked well since.

The problems experienced during this field trial were readily handled and caused minimal disruption, since the previous unit (the mercury arc valve) could be placed back in service in a matter of hours. The lessons learned are valuable and demonstrate the importance of carefully monitored field trials for new systems. *Project Manager: Ben Damsky*

DISTRIBUTION

Semiconducting materials for cable insulation shields

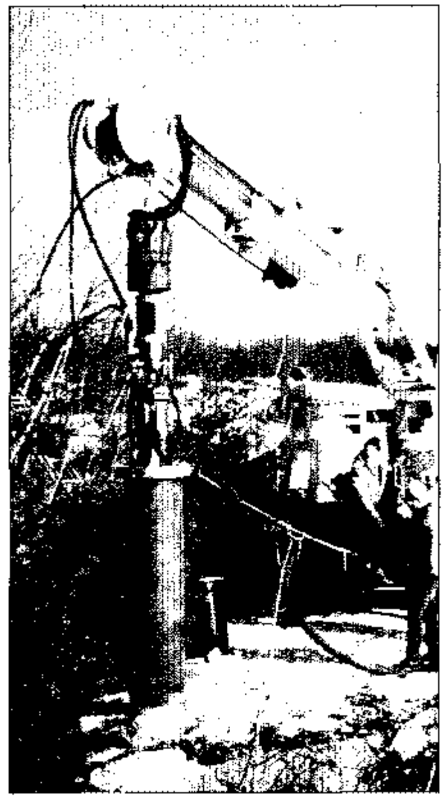
Conventional semiconducting materials used in extruded cables employ conductive carbon black dispersed in a polymer to achieve the required semiconducting properties. Cost and technical considerations make this choice quite practical; indeed, no other options are readily available today.

However, carbon black in the semiconductive layer of an insulation shield serves as a barrier to far-infrared (FIR) light. Therefore, it is not possible to use FIR light in a laser system developed for EPRI to more accurately inspect finished cables for voids and contaminants. If a carbon-black-free system could be developed, it would open up new avenues for inspecting cables and improving quality. The development of such a system is the subject of a new research project (RP2780).

Substitutes for carbon black are not common; nevertheless, two areas seem worthy of study: conducting polymer blends and selected metallic fillers. Questions regarding stability, doping, mixed-system behavior, and, of course, FIR transmission will be addressed. Westinghouse Electric Corp. will be the prime contractor, with Reynolds Metals Co. as subcontractor.

The use of metallic fillers raises another set of questions, and EPRI plans to enter into negotiations with 3M Co. to explore this area. *Project Manager: Bruce Bernstein*

Figure 5 After it reaches the desired depth, the rock hole drill is removed, leaving a core that can be broken at the base with a hydraulic wedge.



Rock pole-hole drill

Final tests of EPRI's rock hole drill (RP2209) have successfully demonstrated its ability to penetrate dense lava at a rate of 16–20 in (41–51 cm) an hour. The rock-cutting tool, called RAM (for rock auger method), previously penetrated granite at the same rate.

The drill is both simple in operation and easy to apply. Mounted in the same position as an auger on a standard digger derrick truck, an 18-in-long (46-cm) steel barrel is fitted with two hydraulic percussion drills. As the barrel rotates, the drills cut an annular kerf in the rock (Figure 5). Spoils are sucked away by a vacuum system. After reaching the desired depth, the barrel is removed; then the core is broken at the base with a hydraulic wedge and removed. A clean, uniform hole is left for the pole and backfill.

A 4-minute videotape on the drill is available to member utilities from EPRI's Corporate Communications Division. *Project Manager: T. J. Kendrew*

R&D Status Report
ENVIRONMENT DIVISION

George Hidy, Vice President

ORGRISK: EXPOSURE ASSESSMENT SCREENING TOOL

There is increasing public concern about the potential contamination of groundwater by organic chemicals. In the utility industry various organic compounds are produced in the course of combustion processes, are used in control technologies, and are stored in underground tanks. Hence the proper disposal of organic wastes is an important utility concern. EPRI is helping the industry meet this challenge by producing exposure assessment models for evaluating potential risks from chemical spills and storage tank leaks. One such model is ORGRISK, which can be used to assess human exposures from potential water and soil contamination by coal gasification residues or by spills resulting from utility pole treatment practices (RP2634-1).

It is estimated that in the United States before World War II, there were well over 1000 plant sites where gas was manufactured from coal or oil. (The number of active facilities decreased during the 1950s after the construction of interstate pipelines for the transmission of natural gas.) The wastes and by-products of gas manufacturing were in some cases disposed of on-site. They included tar residues and sludges, spent-oxide wastes, and ash materials. Residues from materials handling, by-products recovery, and wastewater disposal operations were also disposed of on-site. Today's electric utilities have inherited many of these disposal sites.

The composition of gas plant wastes is highly variable and depends on the type of process that was used. Typically gas plant tars are composed mainly of polynuclear aromatic hydrocarbons (PAHs), with smaller amounts of phenolic and light aromatic compounds (e.g., benzene and toluene). Spent-oxide wastes may contain high levels of sulfur, cyanide, and ammonia compounds bound with iron. Ash materials contain trace metals. The potential human health and environmental effects associated with chemicals at gas plant sites can range from exposure to possible carcinogens (in the case of PAHs) to odors in water supplies (in the case of phenolics).

Utility-owned pole treatment facilities pose similar problems. For years the electric utility industry has used preservatives to protect wood transmission poles. Treating wood increases life expectancy five times or more and reduces the overall costs for pole replacement. Of the major types of preservative, pentachlorophenol (PCP) and creosote have been used most extensively. Preservatives are also used in groundline treatment—that is, the in-place treatment of poles just above and below the ground surface. Groundline treatment can extend the life of a pole by 20 years or more.

Releases of wood preservatives have occurred at pole treatment and storage facilities and in conjunction with groundline treatment. Soil and groundwater contamination appears to be the most common problem associated with such releases. Site cleanup is complicated by the fact that PAHs and PCP tend to adsorb to soil. Once these compounds have contaminated an aquifer, it is expensive and time-consuming to remove them; moreover, there are questions about acceptable options for disposal after they are removed.

The utility industry needs information and techniques for use in assessing (1) the potential for water and soil contamination at gas plant sites and pole treatment sites and (2) the potential exposure levels associated with various cleanup options. Therefore, under RP2634-1, EPRI sponsored the development of the ORGRISK model and software. ORGRISK provides screening-level (i.e., order-of-magnitude) estimates of chemical concentrations in soil, groundwater, and surface water and of associated exposure levels. Because simple, analytic equations are used to calculate the chemical concentrations and exposure levels, time and data requirements are minimized; also, the equations can be solved with a personal computer spreadsheet program, such as Lotus 1-2-3. (Research is being conducted under RP2879 to develop a fundamental understanding of the transport and fate of organics in the subsurface and surface environment and to develop a more detailed set of models for predicting these phenomena.)

ORGRISK currently consists of four spreadsheet templates (i.e., sets of equations). The first is the contamination potential template. It is used to estimate the contamination potential posed by a chemical release to soil or groundwater and to evaluate potential soil cleanup options. The other three templates are used to estimate exposure in scenarios in which contaminated groundwater is treated; they apply to different groundwater treatment and disposal options.

The contamination potential template covers two types of release. The first is a release to soil above the water table (i.e., in the unsaturated zone); in such cases the subsequent migration of chemicals through the unsaturated zone could lead to groundwater contamination. The second type of release is a release directly to groundwater, which might occur at a site where the water table is shallow or at a facility directly in contact with groundwater (e.g., a landfill, evaporation pond, or seepage pit). With this type of release, subsequent chemical migration in the groundwater could lead to the contamination of a water supply well or of nearby surface water.

The equations making up the contamination potential template are based on a number of simplifying assumptions. One important assumption is that chemical migration occurs only in the aqueous phase (i.e., when the chemical is dissolved in water). The template is not applicable to nonaqueous-phase migration (the movement of a separate, immiscible phase), which can occur at gas plant and pole treatment sites, particularly in the immediate vicinity of the contamination source. Another important simplifying assumption is that the release and the resulting soil, groundwater, and surface water concentrations do not vary with time. The template is thus applicable primarily to long-term conditions.

The contamination potential template can also be used to evaluate options for soil cleanup. In this case, rather than estimating the chemical concentrations in groundwater and surface water associated with a release, the user selects an acceptable groundwater or surface water concentration on the basis of available criteria and then uses the template to estimate the release. In essence, the template "back-calculates" the release concentration that would produce the selected groundwater or surface water concentration. Once this target release concentration has been estimated, it can be compared with the actual release concentration to determine what level of cleanup is required, if any. The cleanup options are (1) excavation, which would lead to a reduction in the source concentration, and (2) capping, which would reduce the rate of recharge and the associated rate of chemical leaching to groundwater.

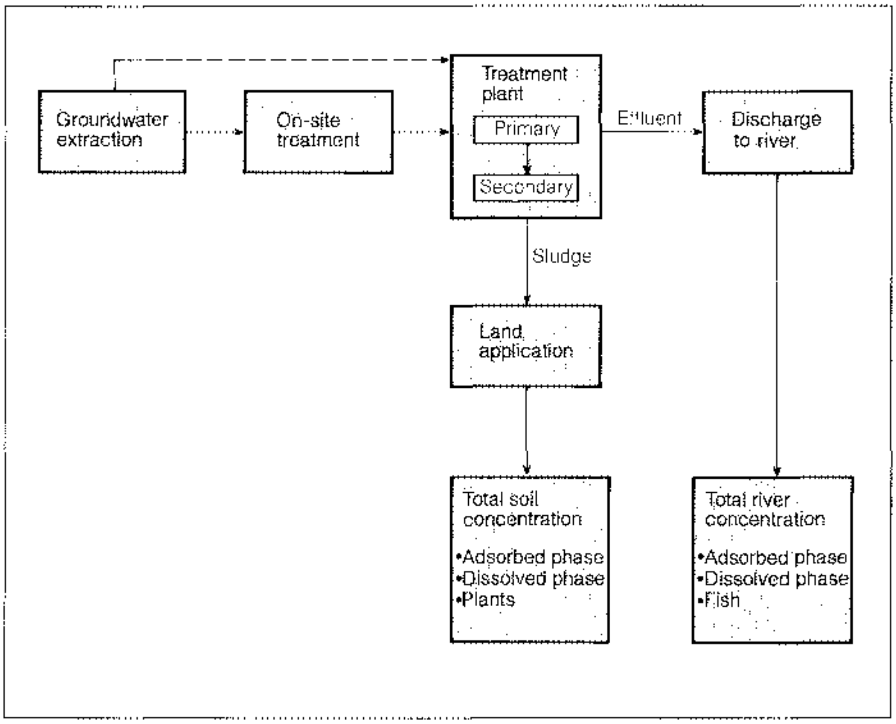
Because there are a number of possible options for handling contaminated groundwater, three groundwater cleanup templates were developed for ORGRISK. The options differ as to whether the groundwater is treated before disposal and as to the type of disposal. The groundwater treatment options that can be assessed with ORGRISK are on-site treatment with activated carbon, primary treatment at a wastewater treatment plant, and secondary treatment at the treatment plant. The disposal options that can be assessed are discharge to a river, land application, and reinjection.

The treatment and disposal options were combined as follows, and a template was developed for each combination.

- Groundwater extraction, with or without on-site treatment, and discharge to a nearby river
- Groundwater extraction, with or without on-site treatment, followed by treatment at a local municipal wastewater plant
- Groundwater extraction followed by on-site treatment and reinjection to an aquifer

Each groundwater cleanup template consists of equations that relate the chemical concentrations in soil, groundwater, and surface water, as well as equations that describe the effects of different treatment and disposal options. For example, Figure 1 illustrates the second template, under which groundwater is extracted and sent to a local municipal wastewater treatment plant, with or without on-site treatment. The plant can perform primary treatment only or both primary and secondary treatment; its effluent is discharged to a river. For purposes of exposure assessment, the total chemical concentration in the river is broken down into three parts—the adsorbed-phase concentration, the dissolved-phase concentration, and the concentration in fish. Sludge from the treatment plant is disposed of through land application. Because it is necessary to estimate exposure levels associated with the accumulation of chemicals in soil and plants treated with sludges, the soil concentration is broken down into the adsorbed-phase concentration, the dissolved-phase concentration, and the concentration in plants.

Figure 1 This ORGRISK framework is used to evaluate groundwater cleanup involving extraction by wells and discharge to a wastewater treatment plant. It allows for the option of on-site treatment and for two levels of treatment at the plant. Chemical concentrations are estimated at each step in the scenario, and the final river and soil concentrations are broken down by phase.



Like the contamination potential template, the groundwater cleanup templates provide estimates of steady-state concentrations. It is possible, however, to evaluate how concentrations will change as groundwater cleanup proceeds. For example, given the frequency of land application, the user can estimate the accumulation of a chemical in soil as a result of multiple sludge applications.

All four ORGRISK templates are structured for implementation with the standard personal computer spreadsheet program Lotus 1-2-3. A spreadsheet program was selected because most utility engineers are familiar with, and have access to, this type of program; because the modular structure of a spreadsheet is consistent with the structure of each template; and because most spreadsheet programs offer interactive features and graphics packages that facilitate the use of the method.

Many utilities are now conducting investigations of gas plants, pole treatment sites, and other sites where organic wastes may be present. ORGRISK is an easy-to-use screening tool that can help them estimate potential exposure levels associated with a range of soil and groundwater cleanup options. It is currently being tested by several host utilities and will be available from the Electric Power Software Center in the near future. *Project Manager: Abraham Silvers*

QUANTIFYING ATMOSPHERIC DEPOSITION

Since the mid-1970s the electric utility industry has actively sponsored research related to the issue of acidic deposition. In 1981 an ad hoc group of 35 companies established a monitoring network known as the Utility Acid Precipitation Study Program, or UAPSP, to extend an EPRI study begun in 1978. EPRI provides technical management for UAPSP, and the Edison Electric Institute handles administrative functions. Twenty-one sites throughout the eastern and central United States are in operation. This report summarizes the findings to date, as well as the continuing observations planned through 1989 as part of an international effort to evaluate new regional air quality models.

The objective of UAPSP is to establish the temporal and spatial variability of precipitation chemistry. Samples are collected daily whenever precipitation occurs and are sent to a central laboratory where they are analyzed for pH, conductivity, acidity, and concentration of sulfate, nitrate, chloride, ammonium, sodium, potassium, calcium, and magnesium. Six of the sites have been in operation since late 1978 and have provided over seven years of data.

Data quality

Because trends in precipitation chemistry can be difficult to identify, knowing the quality of data is extremely important. The precision of the UAPSP data is established by analyzing samples collected by identical, side-by-side samplers, by analyzing the same sample twice, and by continual analysis of standardized solutions. Information on accuracy is obtained by verifying that all the precipitation is sampled, by assessing changes in composition before arrival at the laboratory, and by verifying laboratory performance with reference solutions. Such quality control has shown that between 90% and 99% of the days with precipitation are sampled by the network each year, that sample contamination is not a major contributor to measurement uncertainties, and that measurement error (based on data from side-by-side samplers) is usually less than 10% of the annual median concentration for the major constituents (hydrogen, sulfate, nitrate, and ammonium ions). These and other results confirm that consistent, high-quality measurements are being obtained.

One important criterion of the accuracy of the network data is collection efficiency—that is, whether the samples collected represent the composition of the water that fell. This is established by comparing the amount of precipitation collected in the sampling container and the amount measured with a rain gage. For rain samples the collection efficiency for individual sites ranged from 86% to 179% annually, with a seven-year mean efficiency for all sites of 103%. But for snow samples the range was much larger, from 25% to 251%, with a seven-year overall mean of 83%. These discrepancies between samplers and rain gages will be accounted for when estimating the uncertainty associated with precipitation amount. The largest deviations seem to occur under very windy conditions and with snow. UAPSP researchers are now testing improved techniques for collecting snow, which may be needed in areas where more than 20% of the winter precipitation is frozen. This special study will also indicate whether the samples collected have representative precipitation compositions.

What the data show

A cursory analysis of the data from 1979 through 1985 shows remarkable constancy in annual wet deposition, both networkwide and within subregions. Wet deposition of sulfate and nitrate has been virtually constant over seven years for the Midwest, the Northeast, and the Southeast. There are distinct differences between subregions, however, as illustrated for sulfate in Figure 2.

Precipitation acidity (pH) is widely thought to be an indicator of potential environmental damage. It is now known, however, that looking at pH alone gives an incomplete picture. The chemical composition of precipitation, not just its acidity, must be considered.

When the concentrations of the major ions in precipitation—sulfate, nitrate, ammonium, and calcium—are examined and compared with pH, striking subregional patterns emerge. From 1982 through 1985 the Midwest and the Northeast had approximately the same pH levels, with a four-year average of 4.29. (The Midwest is represented by sites in Indiana, Kentucky, Ohio, and West Virginia; the Northeast, by sites in Pennsylvania, New York, Massachusetts, and Vermont.) Yet over that same period, sulfate concentrations for the Midwest were 30% higher. This apparent inconsistency is resolved when the concentrations of the other major ions are examined. Nitrate concentrations for the two subregions were similar, but both the ammonium and the calcium concentrations were much higher in the Midwest (approximately 40% higher for ammonium and 130% higher for calcium).

Another interesting comparison is between the southeastern and west central subregions. (The west central subregion is represented by sites in South Dakota and Kansas; the southeastern, by sites in Texas, Mississippi, Alabama, Georgia, Tennessee, and North Carolina.) Data from 1982 through 1985 indicate that the two subregions had approximately the same annual sulfate concentrations. But nitrate, ammonium, and calcium concentrations were approximately 40%, 180%, and 190% higher, respectively, in the west central subregion. As a result, acidity was approximately 400% lower for that subregion than for the Southeast.

These comparisons illustrate the pitfalls of using only one factor, such as sulfate or pH, as an indicator of precipitation chemistry.

In addition to subregional differences, pronounced seasonal trends in concentration are apparent in the data. Sites throughout the network have the highest acidity and sulfate concentrations in the summer and the lowest in the winter or fall. Ammonium tends to be highest in the summer or spring. The seasonal patterns for nitrate are more variable across the network, but concentrations tend to be highest in the summer or spring (for some sites they peak in the winter also). The higher sulfate and nitrate values in the spring and summer may be due to higher levels of oxidants and warmer temperatures, which accelerate the oxidation of sulfur dioxide and nitrogen oxides.

Special studies

In addition to the routine monitoring operations, short-term special studies have been conducted under UAPSP. One such study compared samples collected weekly with those collected daily. Most monitoring networks sample at one of these frequencies. Because combining data sets might enhance their usefulness, it is important to know the comparability

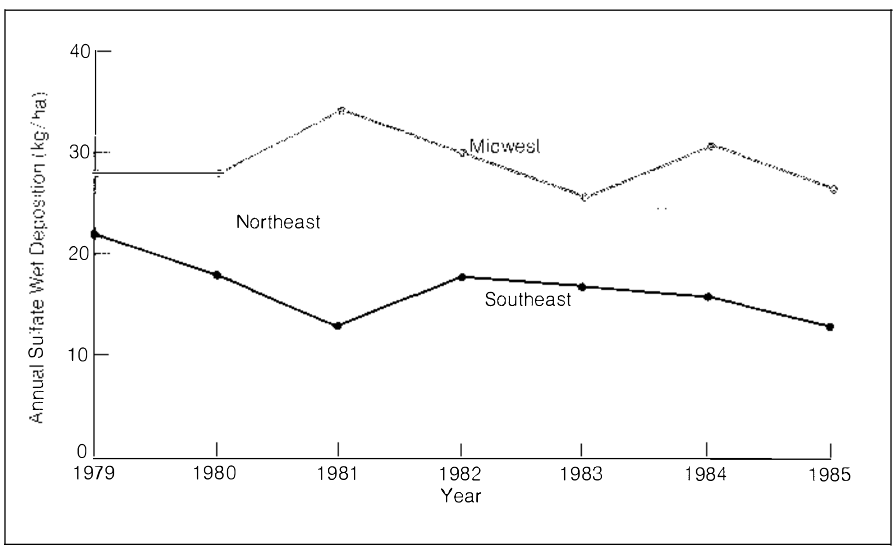


Figure 2 Annual wet deposition of sulfate for three UAPSP subregions. No upward or downward trends are evident; however, differences between subregions are notable.

of weekly and daily data.

A comparison of weekly and daily precipitation-sampling results was conducted at the Georgia, Kansas, and Vermont UAPSP sites in a study cofunded by UAPSP and EPA. As part of this one-year study (1983–1984), two pairs of identical precipitation samplers were deployed at each site. For one pair, samples were collected daily; for the other, weekly. The study design overcame some of the limitations of previous studies in that identical sample-handling procedures and a single laboratory were used.

The daily data were grouped by week for comparison with the weekly data. The study found that there are statistically significant differences in reported concentrations between the weekly data and the daily data, but that these differences are not large. The concentrations for most constituents were somewhat higher in the weekly samples than in the composite weekly data based on daily samples. Possible explanations for these biases are greater evaporation from weekly samples, contamination during the seven-day storage in the collector, sample instability, and the contribution of trace samples with highly concentrated constituents. Trace samples (i.e., from events yielding volumes less than 30 ml) were included in the weekly samples; they were not accounted for in the weekly composites, however, because trace samples collected daily are too small for chemical analysis.

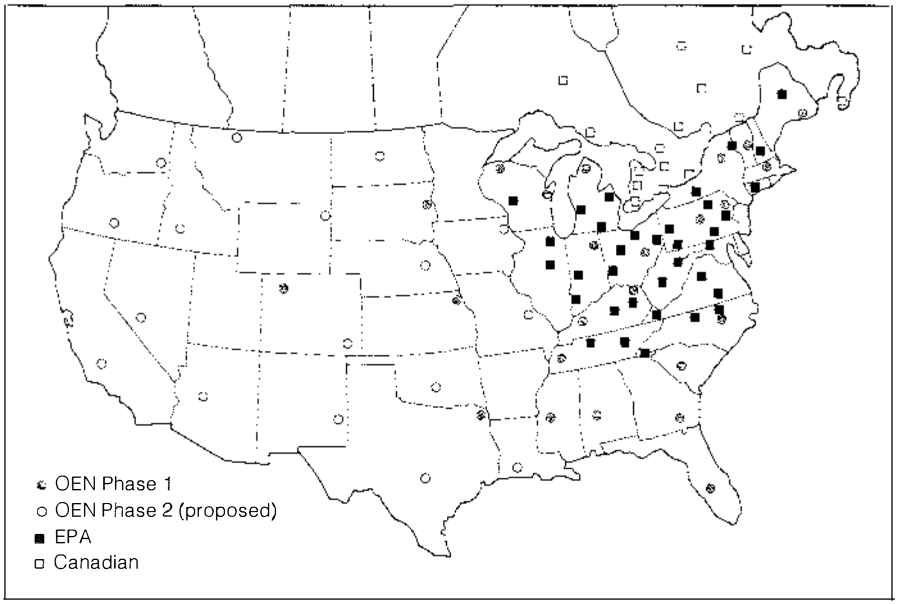
The study also found that the ability to detect annual trends in precipitation chemistry is enhanced by daily sampling. Taken individually, daily and weekly data sets can provide consistent spatial distributions; combining them may alter or add noise to these distributions.

Another exploratory study examined how precipitation chemistry is related to various meteorological parameters. A main objective was to quantify the variability in precipitation composition attributable to single meteorological factors and the variability attributable to various groups of factors.

One part of the study examined the wind direction associated with each precipitation sample at all the eastern UAPSP sites to determine its influence on sulfate concentration. This analysis found no consistent site-to-site pattern of sulfate transport. Hence wind direction alone does not appear to be an adequate indicator of sulfate origin.

Other study results suggest that the meteorological factors with the greatest influence on precipitation chemistry are precipitation type, wind field, upwind stagnation, occurrence of precipitation en route to the receptor, and precipitation amount and intensity. However, the study was unable to resolve the relatively large variability in chemical concentrations in precipitation observed within groups of meteorological factors. More chemical measurements in clouds and on the ground are needed to understand the causes of this variability.

Figure 3 Through its Operational Evaluation Network, EPRI will participate in a coordinated effort to collect atmospheric deposition data for use in evaluating regional air quality models. Data will also be provided by the EPA's monitoring network and two Canadian networks.



Other special studies have evaluated acidity measurements, nitrate and nitrite concentrations, the relationship between cloud type and precipitation chemistry, and spatial patterns (by means of statistical, or kriging, analysis).

Future data development

UAPSP receives approximately 15 requests for data each year from research organizations, state and federal agencies, utilities, and the media. The data are also entered into the Acid Deposition System (ADS), the national data management system established by EPA. Reports on UAPSP operations, data, and special studies are being published and are available from the UAPSP Reports Center (telephone: 301-670-0100).

Although the main UAPSP objective is to characterize wet deposition, the data obtained are also being used in analyses to relate emissions to deposition. Both empirical and theoretical regional air quality models require such data for development and evaluation. Current precipitation networks have a major limitation for this application, however: they supply information only for wet deposition and not for dry deposition, which has been estimated to account for approximately 50% of the total material deposited. There is a lack of dry deposition data because no reliable measurement method is available.

Unless comprehensive deposition data can be obtained, it is possible that models like the federal government's RADM (regional acid deposition model) will be used for assessing emission controls after only limited testing and evaluation. To satisfy the data requirements for model evaluation, EPRI is modifying and expanding the UAPSP network. The new network, known as the Operational Evaluation Network (OEN), will collaborate with similar networks operated by the U.S. EPA, the Canadian Atmospheric Environment Service, and the Ontario Ministry of the Environment (Figure 3). In addition to monitoring wet deposition, these networks will make meteorological and aerometric measurements, which will be used to calculate dry deposition. Thus determinations of total deposition ought to be possible. Not only will the new networks permit the evaluation of theoretical models, they will also be of great value for empirical analyses of emissions-to-receptor relationships.

OEN will take over operations from the UAPSP network in January 1988 and is scheduled to operate for a minimum of two years. In the future the 24-site network may be expanded into the western states. The data from UAPSP and the follow-on networks will provide valuable information about the characteristics of atmospheric deposition. This information is crucial for understanding how emissions are related to deposition and for ensuring that regional air quality models are evaluated against real-world measurements. *Project Managers: Mary Ann Allan and D. Alan Hansen*

R&D Status Report
NUCLEAR POWER DIVISION

John J. Taylor, Vice President

ULTRASONIC INSPECTION OF CCSS

Centrifugally cast stainless steel (CCSS) is often used for main coolant piping in PWRs. Unfortunately, the characteristics of CCSS that account for its structural strength and durability also make it difficult to inspect with standard ultrasonic techniques. The manufacturing process—centrifugal casting—creates an anisotropic and inhomogeneous material that scatters ultrasonic pulses in unpredictable ways. In addition, ultrasonic pulses are severely attenuated before reaching the inner depths of a pipe wall, both because of the grain structure and because of the wall thickness, which in PWR applications is typically 2–3 in (5.1–7.6 cm) with pipe diameters on the order of 30 in (76 cm). EPRI is funding research to develop improved techniques for inspecting CCSS piping.

The CCSS inspectability problem is being approached in many ways. Metallography, modeling, experimental ultrasonics, signal processing, and inspection strategy are being combined into a program that will achieve the goal of improved CCSS inspection capability. Results are expected over the next year that will lead to increasingly reliable and effective field methods for the ultrasonic testing of CCSS components.

A seminar on the ultrasonic inspectability of CCSS was held recently at EPRI's Nondestructive Evaluation (NDE) Center in Charlotte, North Carolina. The seminar served three main purposes: (1) to establish the status of CCSS inspectability, (2) to critically review approaches proposed by a panel of NDE experts for improving CCSS inspectability, and (3) to identify those approaches that have a high probability of success in a reasonable time and at a minimal research cost. The seminar was attended by 20 people engaged in ultrasonic NDE. The following review of the seminar discussions provides an overview of the CCSS inspectability problem.

The material itself, CCSS, was described and characterized by several seminar participants. CCSS is highly anisotropic, inhomogeneous, and highly attenuative to ultrasonic sound waves. Its grain structure can be divided roughly into three classes: columnar, equiaxed, and a combination of the two.

It is anticipated that appropriate ultrasonic techniques can be configured to deal with the inspection of each of these CCSS structures. In field inspections, however, the grain structure is unknown, which complicates the selection of a proper ultrasonic technique. This is particularly problematic for CCSS piping inspections at PWR plants. Often information about the material used in an installation is unobtainable. Critical ultrasonic inspection parameters, such as material thickness and wave velocities, are unknown, as are metallurgical characteristics and the types of flaws they make the material susceptible to.

Work at the NDE Center (RP1570-2) and at Drexel University (RP2405-18) has explored various ways of ascertaining the predominant grain structure of CCSS samples. Similar efforts are being conducted at Battelle, Pacific Northwest Laboratories and at Argonne National Laboratory. The goal of all this work is to identify a set of ultrasonic hardware and methods that can reliably estimate the grain structure of CCSS.

Advanced signal-processing techniques are also being explored. This research has succeeded in adapting radar techniques to reliably differentiate grain structures in common steels (RP2405-22); grain structure shows up much like the background clutter that is distinguished from a target in military radar applications. Linear arrays—transducers aligned contiguously in strips—are being considered as a possibility for upgrading the front-end signal acquisition hardware. Engineers at Southwest Research Institute will be investigating the use of low-frequency arrays for obtaining better signals from CCSS (RP2405-20). Such improved signals could make it easier to develop grain characterization techniques.

Although no CCSS defects have been found in operating U.S. plants, service-induced defects—thermal fatigue and mechanical fatigue cracks—are nonetheless postulated. The important component integrity variables associated with such cracks, if they occur, are their location, orientation, and size. These variables must be accurately estimated with ultrasonics, but again the variability of CCSS grain structure makes this a difficult task.

Ultrasonic determination of crack location, size, and orientation depends critically on knowing both the ultrasonic beam direction within the material and the ultrasonic wave velocities. Crack size estimates depend especially on signal clarity and resolution. The way in which ultrasonic field characteristics are altered by CCSS is another important aspect of CCSS inspectability.

Insight into the distortion that CCSS causes in ultrasonic signals is being gained through results from three EPRI research projects (RP2405-18, RP2687-1, and RP2687-2). These projects cover, respectively, numerical, analytic, and finite-element approaches to modeling sound wave interactions in anisotropic, inhomogeneous materials. Each approach has advantages and disadvantages; combining the useful results from all the methods can give a better picture of CCSS effects than can the results from any one alone. Each method can model reflectors within the material of interest. As the models converge to a reliable and accurate simulation of field conditions, ultrasonic inspectors will be better equipped to interpret signals from a given CCSS component.

The quality of the models depends on the use of proper values for such material properties as crystalline lattice structure, wave velocities, and acoustic impedances. The work of those studying CCSS characterization will contribute greatly to the attainment of proper material property constants.

Samples of CCSS are invaluable for this work. Westinghouse Electric Corp., through the Westinghouse Owners Group (WOG), has fabricated 75 samples of CCSS that incorporate a variety of grain structures and defects. WOG has made these samples available to the NDE

Center, where they will be used in several ways for model validation. Model results must be correlated with experimental data to define their domain of application and their limits. To further refine the models, researchers can iterate between the models and experimental data. In addition, the samples' material properties can be measured and used as input data for models.

The CCSS samples are also used to qualify proposed inspection techniques. Therefore blank, or defect-free, samples are included in the collection. It is important that any field technique be able to distinguish and discount the spurious ultrasonic defect signals produced by the grain structure of CCSS. In yet another use, the CCSS samples can serve as test material for training inspectors.

Recognizing the limitations of standard ultrasonic techniques for inspecting CCSS, researchers recommend a three-pass approach. The first two passes would involve material characterization and the selection and application of the ultrasonic technique most appropriate for the material at hand, with emphasis on finding defects of significant size. Georgetown University is investigating the use of Rayleigh and Lamb waves—subsurface waves that can detect defects that penetrate into the outer 20% of a component's wall thickness—for this purpose (RP2405-23). After the big defects are located, the third pass would concentrate on finding smaller defects; this is the primary focus of current research. *Project Manager: Michael J. Avioli, Jr.*

CONFIRMING THE SEISMIC RUGGEDNESS OF PLANT EQUIPMENT

A number of EPRI research projects are under way to help the owners of nuclear power plants demonstrate the earthquake ruggedness of plant safe-shutdown equipment. The projects, which use experience from actual earthquakes and tests that simulate earthquakes, measure the seismic ruggedness of equipment, including such weak links as relays that can chatter and equipment anchorages that can pull out of concrete floors and walls. Results from this research are being used by EPRI member utilities and members of the Seismic Qualification Utilities Group (SQUG), which has pioneered the use of earthquake experience for checking the seismic adequacy of equipment. With EPRI's help, SQUG is now working with NRC to develop an acceptable set of criteria and procedures for use in upcoming plant inspections.

Recently the owners of 72 older operating nuclear plants received a "generic letter" from NRC requiring an evaluation and inspection of equipment to ensure that each plant could be brought to a safe, hot shutdown condition during or after a design-basis earthquake (DBE). Although all nuclear plants have been designed for safe-shutdown earthquakes (SSEs), those that began operating in the 1960s and early 1970s were not designed to today's more rigorous earthquake standards.

The generic letter outlines the actions utilities must take to ensure plant safety in the event of an earthquake. It is precedent-setting in that many of the affected utilities played an active role in developing, with NRC, a mutually acceptable approach for resolving the issue. The innovative approach involves the use of actual earthquake experience as the basis for evaluating the seismic adequacy of equipment.

SQUG, an owners group formed specifically to sponsor such seismic qualification, has compiled information on the performance of thousands of items of industrial equipment subjected to earthquakes in the United States (California) and in several other countries in North and South America. Since much of this equipment is similar or identical to that used in operating nuclear plants, the nuclear plant equipment can be seismically qualified by comparison with the industrial equipment data. This approach is much less costly than qualification using the more traditional shake-table method of testing.

EPRI has sponsored several research projects to provide technical information to support SQUG in resolving the qualification issue, and recently several additional projects have been authorized with substantial cofunding from SQUG. The EPRI research addresses technical issues not entirely covered by the SQUG earthquake experience data base. All seismic qualification projects are coordinated through the EPRI Seismic Center.

Equipment ruggedness

An item of equipment is seismically rugged if it can perform its safe-shutdown function during or after a design-basis earthquake. Most critical equipment needs to operate only after the shaking stops; but several components, such as certain electrical relays, must be functional (i.e., must not chatter or change state) *during* the earthquake. The SQUG earthquake experience data base can be used to check the operability of equipment after an earthquake, but only in some cases can that information be used to infer operability during the shaking. One EPRI project has compiled qualification shake-table data to construct generic ruggedness levels for many equipment classes, including relays. Another is investigating the plant relays whose operability is essential during an earthquake.

The test data compilation effort (EPRI NP-5223) examined motion measurements from tests on many classes and models of equipment from different manufacturers. The equipment classes included motor control centers, switchgear, motor-operated valves, and relays. Operability was monitored during and after the tests. The resulting generic equipment earthquake ruggedness spectra essentially represent earthquake ratings for the operability of the various equipment classes. For each class the study identifies a checklist of equipment characteristics, or inclusion rules, that ensure that a given piece of nuclear plant equipment is similar to the tested equipment and is therefore covered by the generic ruggedness spectrum. A typical ruggedness spectrum, for emergency power batteries mounted in double-railed racks, is shown in Figure 1. The batteries are qualified if their input motion is less than the generic ruggedness spectrum and if all inclusion rules are satisfied.

The equipment classes most sensitive to earthquake motion (those with the lowest ruggedness) are cabinets that contain relays. The mechanical arms of relays are subject to chatter that can produce momentary breaks in control or in instrumentation signals. This chatter (or even worse, earthquake-induced change of state) could produce erroneous control signals or could lock out important circuitry and prevent it from performing its safe-shutdown function.

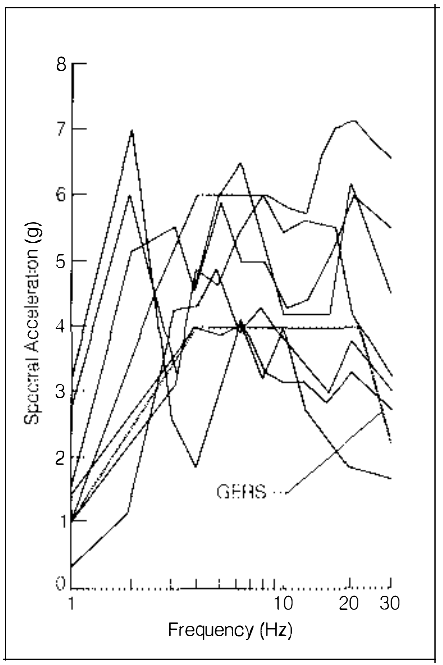


Figure 1 A generic equipment ruggedness spectrum (GERS) is developed by compiling and evaluating shake-table qualification test data (black curves). The GERS shown here indicates the capacity of plant storage batteries mounted in double-railed racks to withstand earthquake shaking.

An EPRI-sponsored relay functionality study is providing utilities with a systematic methodology for plant-specific identification of essential relays—those whose malfunction during an earthquake could inhibit safe shutdown (RP2849-1). This safe-shutdown systems analysis, together with the relay ruggedness spectra derived from the test data compilation, will facilitate plant inspections and minimize the number of relays subject to retrofitting as a result of the plant evaluations. The relay functionality methodology, honed by two trial plant applications, will be available by mid-1987.

Anchorage guidelines

The experience data base showed that damage incurred during an earthquake was often caused by inadequate equipment anchorage to concrete floors or walls. Equipment earthquake capacity is usually controlled by failure of the anchor bolts or welds at the equipment mounting. EPRI has performed a study that provides utilities with practical guidelines for evaluating the adequacy of equipment anchorages during plant inspections (NP-5228).

The guidelines consist of (1) screening tables that give anchorage capacities for many classes of equipment, (2) procedures for inspecting anchorages for proper installation, and (3) a computerized analysis method for specific evaluation of anchorages that do not pass screening during the plant inspection. The guidelines cover concrete expansion anchor bolts, cast-in-place bolts, and welding to embedded structural steel. For expansion anchor bolts, the study generated the most extensive data base of tension and shear test results ever collected. This data base establishes realistic allowable loads for bolts on the condition that their proper installation can be verified by inspection. Equipment earthquake capacities were calculated with an analysis method similar to that used to design anchorages in modern nuclear plants. The guidelines will be used during 1987 for trial plant inspections.

A related study examined the performance of equipment and anchorages at several industrial facilities that had been subjected to California earthquakes (RP1707-15). Researchers used the success or failure of specific equipment anchorages in the study to benchmark the analytically based anchorage guidelines. In all cases, actual performance was consistent with the predictions of the analyses.

Postearthquake investigation

EPRI is continuing the investigation pioneered by SQUG of the earthquake performance of equipment. The EPRI postearthquake investigation program sponsors field trips to earthquake sites by industry experts for the purpose of gathering data on the performance of equipment and structures. The data are used to assess the earthquake capacity of equipment; also, when possible, records of ground and structural motion are obtained. The program draws on the talents of a pool of 30 experts to perform the investigations, with one to five participants chosen for each trip, depending on the type of expertise required.

In addition, EPRI has formed the Utility Contact Network, consisting of representatives from 45 U.S. utilities. UCN members inform EPRI directly of earthquakes in their service areas and provide initial general information on earthquake magnitude, severity, and effect on electric generating facilities. EPRI has access to a similar international network through the Earthquake Engineering Research Institute.

To date, the EPRI program has sponsored five activities, the first being a reconnaissance investigation of the Mexican earthquake in September 1985. A team of experts spent three days in Mexico investigating three power generation facilities and obtaining ground motion records directly from the University of Mexico (NP-4605). Recently a return trip was made to gather data on specific types of equipment for which damage had previously been reported.

EPRI has also sent teams to the North Palm Springs, California, area (July 1986); to El Salvador; and, more recently, to the Bay of Plenty region in New Zealand. In North Palm Springs the EPRI team investigated damage to an electrical substation caused by very strong local ground motion. In El Salvador researchers gathered data for studying the relationship between earthquake magnitude and damage potential. And in New Zealand observations were made of the performance of tanks and industrial electrical equipment. EPRI reports on these investigations will be available this year.

To assist investigators in all aspects of the postearthquake program field visits, EPRI has published a planning and field guide (NP-4611-SR). The guide covers what tools and supplies are needed for such trips, how to gain access to damaged facilities, what information to look for, and how to report it in a consistent manner.

Seismic demand

The gathering of data from earthquake experience has until now concentrated on the structural and operational capacity of equipment to withstand earthquakes. For simplicity, equipment performance has been gauged against measurements or estimates of ground motion. EPRI has recently initiated additional studies of earthquake experience to better understand the *demand* side of the equation—that is, to examine what kind of amplified floor motion the equipment actually experiences inside structures like nuclear plants. It is generally felt that the methods used in plant design to calculate floor motion are very conservative. The most immediate need to reduce that conservatism is to allow SQUG to apply the capacity experience data to higher elevations in a structure, where it is difficult to express equipment capacity directly in terms of ground motion.

This project will collect ground motion and in-structure motion data at U.S. and foreign nuclear power plants and from similar structures that have been subjected to low-level earthquake motion (RP2925). Unlike the gathering of capacity data, the demand study must be limited to facilities similar to nuclear plants (i.e., low-rise, thick-walled concrete structures with massive foundations); further, the buildings must be extensively instrumented. As a result, the data are much more sparse and difficult to obtain. Through cooperative agreements with Japan, EPRI hopes to receive a significant amount of such data from Japanese nuclear utilities that have recorded earthquakes at their plants. The estimates of earthquake motion derived from these data are expected to be more realistic than standard estimates because they will reflect motion actually experienced by plant equipment. The estimates will include both the amplification of ground motion by structures and the frequency range of the amplified motion.

Seismic margin

The data from experience-based investigations have also been used by EPRI in developing methods to evaluate nuclear plant seismic margin (RP2722). The objective is to show, with far less effort than a complete reanalysis, that a nuclear plant can safely shut down after experiencing an earthquake larger than that specified in its design. The possibility of such an earthquake occurring has been suggested by seismologists investigating earthquake hazards in the eastern United States. In the seismic-margin project, the ruggedness data from field experience and testing are being used to specify those levels of motion for which there is high confidence that the structures and components needed for safe shutdown will function (high confidence of a low probability of failure, or HCLPF).

The use of experience to solve current problems regarding the behavior of equipment and systems under earthquake conditions will continue as the data base and consequent insights grow. As these project results become available over the next year or two, EPRI will assist utilities with training and implementation guides to ensure that the full benefits of the research are directed toward resolving seismic qualification issues. *Project Managers: George Sliter and Robert Kassawara*

New Technical Reports

Requests for copies of reports should be directed to Research Reports Center, P.O. Box 50490, Palo Alto, California 94303; (415) 965-4081. There is no charge for reports requested by EPRI member utilities, U.S. universities, or government agencies. Others in the United States, Mexico, and Canada pay the listed price. Overseas price is double the listed price. Research Reports Center will send a catalog of EPRI reports on request. For information on how to order one-page summaries of reports, contact the EPRI Technical Information Division, P.O. Box 10412, Palo Alto, California 94303; (415) 855-2411.

ADVANCED POWER SYSTEMS

Third-Party-Funding Analysis Model for an R&D Combined-Cycle Plant
AP-4922 Final Report (RP2700-1); $25
Contractor: Bechtel Group, Inc.
EPRI Project Manager: A. Dolbec

Development of the Zinc Chloride Battery for Utility Applications
AP-5018 Final Report (RP226-5, -9); $32.50
Contractor: Energy Development Associates
EPRI Project Manager: W. Spindler

Coal Gasification Tests at TVA
AP-5047 Final Report (RP2659-1, -4, -5, -6); $32.50
Contractor: Tennessee Valley Authority
EPRI Project Manager: N. Hertz

Potential Uses for the Slag From the Cool Water Demonstration Plant
AP-5048 Final Report (RP985-9, RP1654-35); $32.50
Contractor: Praxis Engineers, Inc.
EPRI Project Manager: S. Alpert

LaPorte Liquid-Phase Methanol Process Development Unit: Continued Operation in Liquid-Entrained-Catalyst Mode
AP-5050 Final Report (RP317-3); $25
Contractor: Air Products and Chemicals, Inc.
EPRI Project Manager: N. Stewart

Proceedings: Tenth Annual Geothermal Conference and Workshop
AP-5059-SR Special Report; $70
EPRI Project Managers: V. Roberts, M. McLearn

COAL COMBUSTION SYSTEMS

Guidelines for the Evaluation of Seam-Welded Steam Pipes
CS-4774 Final Report (RP2596-7); $1000
Contractor: J. A. Jones Applied Research Co.
EPRI Project Managers: B. Dooley, J. Byron

In-Plant Ash-Handling Reference Manual
CS-4880 Final Report (RP1835-4); $400
Contractor: Ash Systems Engineering, Inc.
EPRI Project Manager: W. Piulle

Assessment of Supercritical Power Plant Performance
CS-4968 Final Report (RP1403-6); $32.50
Contractor: Ebasco Services, Inc.
EPRI Project Manager: A. Armor

Circumferential Cracking of Supercritical Boiler Waterwall Tubes
CS-4969 Final Report (RP1890-4); $25
Contractor: Battelle, Columbus Division
EPRI Project Manager: B. Dooley

Corrosion-Resistant Coatings for Low-Pressure Steam Turbines
CS-5013 Final Report (RP1408-1); $540
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: B. Syrett

Coal-Water-Slurry Transportation Alternatives
CS-5053 Final Report (RP1895-20); $40.00
Contractor: Texas Eastern Engineering, Ltd.
EPRI Project Managers: R. Manfred, C. Derbidge

ENERGY MANAGEMENT AND UTILIZATION

REEPS Code: User's Guide
EM-4882-CCM Computer Code Manual (RP1918-1); $40
Contractor: Cambridge Systematics, Inc.
EPRI Project Manager: S. Braithwait

Annual Review of Demand-Side Planning Research: 1985 Proceedings
EM-5019 Proceedings (RP2279-3); $47.50
Contractor: Battelle, Columbus Division
EPRI Project Manager: S. Braithwait

Price Elasticity Variation: An Engineering-Economic Approach
EM-5038 Final Report (RP863-5); $32.50
Contractor: University of California at Berkeley
EPRI Project Manager: S. Braithwait

Review of Commercial Floor Space Forecasting Methods
EM-5041 Final Report (RP1216-4); $25
Contractor: ADM Associates, Inc.
EPRI Project Manager: C. Gellings

ENVIRONMENT

The Transformer/Capacitor Risk Management Model
EA-4985 Final Report (RP2595-1); $32.50
Contractor: Decision Focus, Inc.
EPRI Project Manager: V. Niemeyer

Center for Environmental Physics and Chemistry Data: Requirements and Specifications
EA-5021 Final Report (RP2262-1); $32.50
Contractor: Systems Applications, Inc.
EPRI Project Manager: I. Murarka

CALENDAR

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

JULY

20–22
International Conference: Hardfacing and Wear
Golden, Colorado
Contact: Howard Ocken (415) 855-2055

23–24
Seminar: Radwaste Management
Boulder, Colorado
Contact: Patricia Robinson (415) 855-2412

AUGUST

25–26
Symposium: Power Plant Valves
Kansas City, Missouri
Contact: Stanley Pace (415) 855-2826

SEPTEMBER

9–11
Annual Review: EPRI's Demand-Side Planning Program
Houston, Texas
Contact: Terry Oldberg (415) 855-2887

15–17
Workshop: Generator Retaining Ring Inspection
Charlotte, North Carolina
Contact: Jan Stein (415) 855-2390

22–24
Condenser Technology
Providence, Rhode Island
Contact: John Tsou (415) 855-2220

23–25
Seminar: Meeting Customer Needs With Heat Pumps
New Orleans, Louisiana
Contact: Sharon Luongo (415) 855-2010

OCTOBER

6–9
1987 PCB Seminar
Kansas City, Missouri
Contact: Claudia Runge (415) 855-2149

13–15
Conference: Effects of Coal Quality on Power Plants
Atlanta, Georgia
Contact: Arun Mehta (415) 855-2895

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