EMF and Human Health

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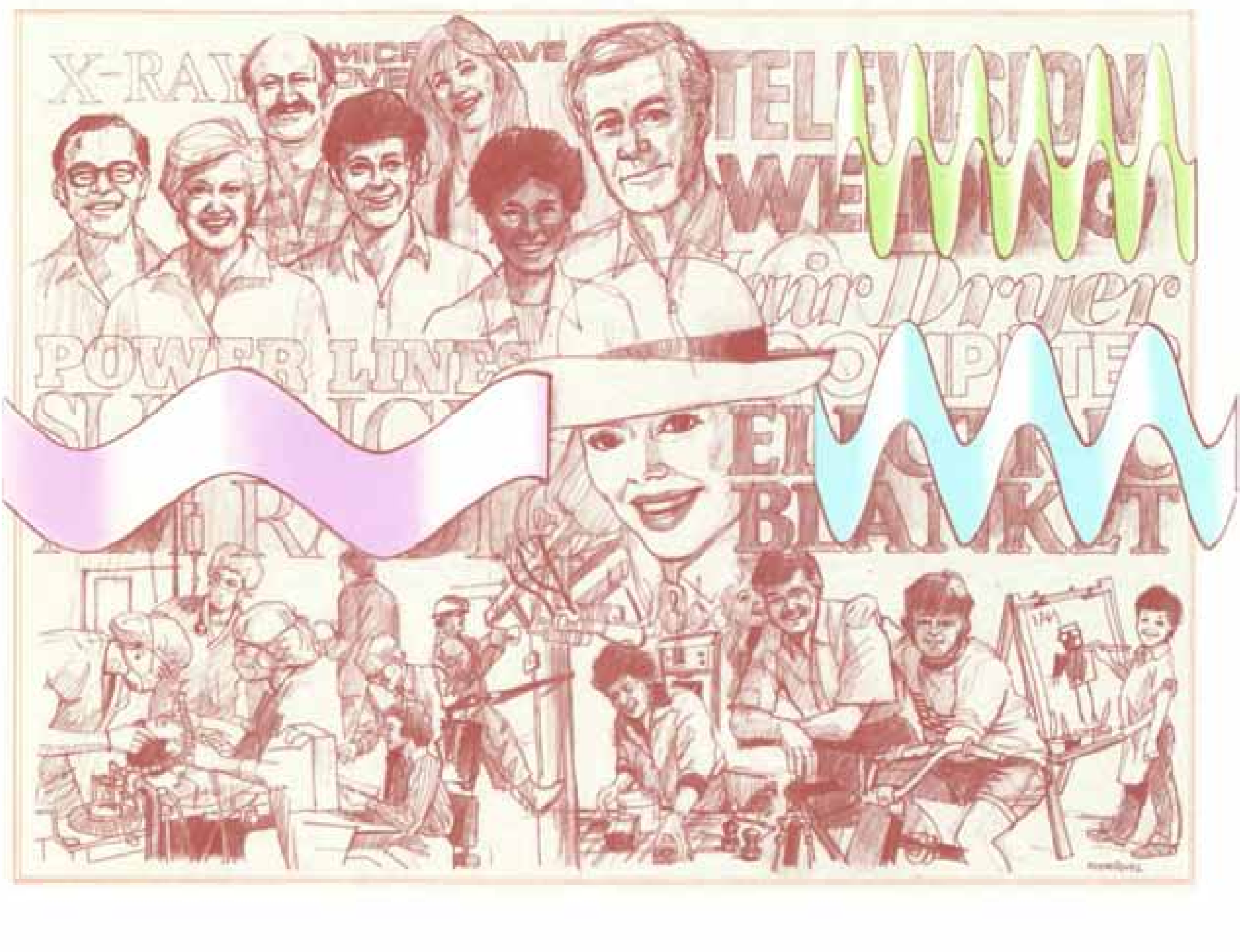

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Cover: Electromagnetic fields are produced by virtually all electric devices, from lights and appliances to power lines. Research is under way to determine whether field exposure poses any risk to human health.

Field Effects—A Call for Research

Electricity is woven inextricably into the fabric of modern society, enhancing our lives in countless ways. Where there is electricity there are low-frequency electric and magnetic fields. These fields are produced by lights, appliances, motors, power lines, and countless other devices that carry or consume electric power.

In recent years concerns have been raised that exposure to low-frequency fields might cause or contribute to adverse health effects, including cancer. Because these fields are so pervasive, it is vitally important that we resolve the question of whether or not they pose a health risk. The only way to gain this understanding is through a comprehensive research effort.

EPRI, individual utilities, and government agencies have sponsored extensive research in this area over the past decade. The evidence gathered to date is fragmentary and inconsistent. Experiments with plants and animals have shown that organisms react in subtle ways to electric and magnetic fields but that these effects do not appear to be harmful, particularly under exposure conditions comparable with those that people are most likely to encounter. The studies on human cancer that found no association between cancer and magnetic fields, as well as those that did, suffer from methodologic limitations that must be resolved in subsequent research before firm conclusions can be reached.

EPRI is expanding its field effects research along lines recommended by the National Research Council to include work in exposure assessment, fundamental study of the biophysical mechanisms of interaction between fields and organisms, and epidemiology. This major, long-term program is built on substantial support from the electric utility industry. By spearheading research in this area, EPRI hopes to stimulate greater national and international scientific interest. A thorough and considered scientific effort should emerge from this work that will provide definitive answers. With such answers in hand, electric utilities, the public, and policymakers will have a rational basis for decision making, a welcome and necessary change from the emotional and often ill-informed process that has characterized the field effects issue in the past.

George Hidy
Vice President, Environment Division

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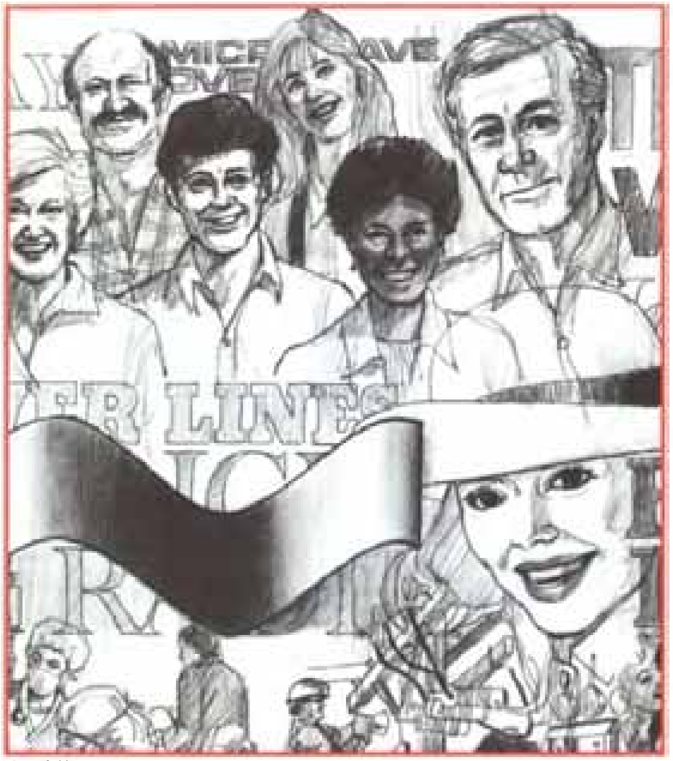

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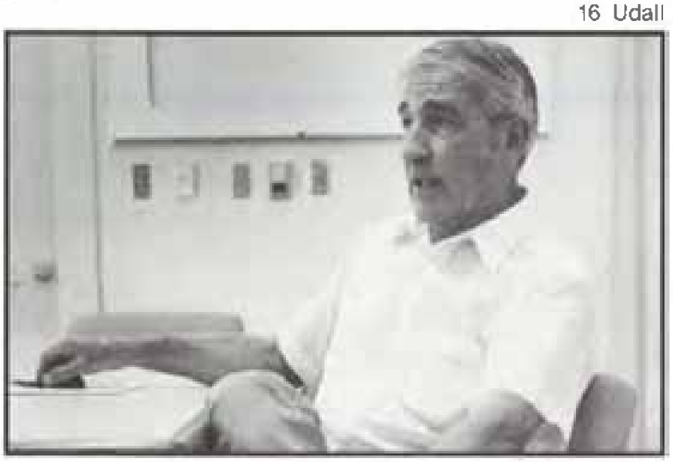


EDITORIAL

COVER STORY

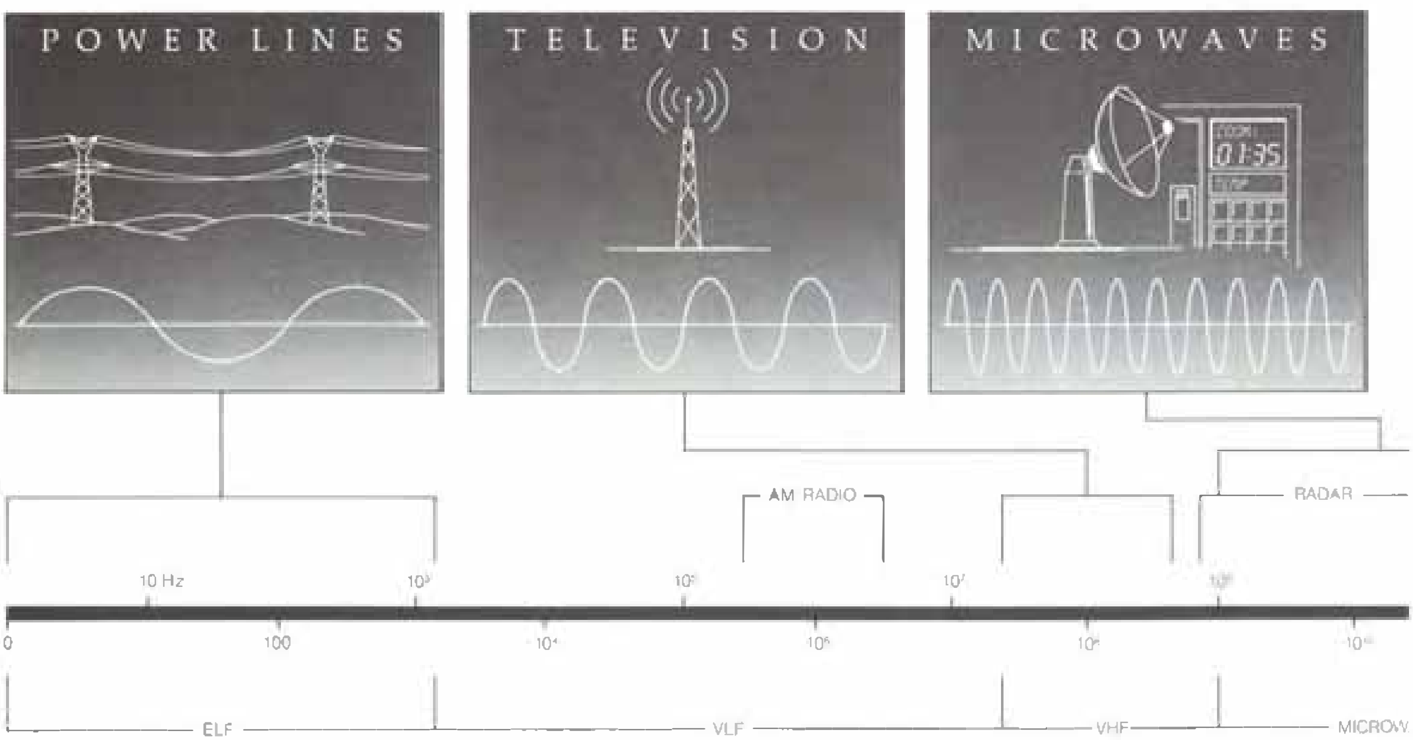
FEATURES

The results of a new study are stirring public concern as to whether childhood cancer may be linked to magnetic fields from power lines. The findings are highly uncertain, however, and the researchers involved maintain that their work raises important questions but falls far short of offering any conclusions or proof.

The hypothesis linking magnetic fields to cancer now rests entirely on correlations from epidemiologic studies. Unlike laboratory studies, which develop hard cause-and-effect relationships from experimental evidence, epidemiology is a science of association, relying on statistics to detect connections between potentially harmful agents and patterns of disease in human populations. About 20 epidemiologic studies have been conducted to date in the field effects area (with conflicting results), but most of the cancer debate stems from two studies in the Denver area.

The first, published in 1979 by Nancy Wertheimer and Ed Leeper, compared the home environments of childhood cancer victims and a control population in an attempt to determine whether any factors related to home environments were associated statistically with the occurrence of cancer. After identifying power lines as a possible factor, the researchers coded the lines outside the homes for high, medium, or low current flow, and postulated that these ratings corresponded, on average, to high, medium, or low magnetic field exposure inside the homes. Measurements they conducted indicated a rough correlation between the wiring code and the measured magnetic fields near the lines.

The Wertheimer-Leeper findings suggested a statistical correlation between cancer and power lines carrying high current loads. Publication of their work touched off widespread scientific dis-



cussion of both their methods and results. Critics argued that they failed to rule out confounding factors, such as air pollution and housing density, that are unrelated to power line fields but might have contributed to cancer. Their wire coding system was also criticized as an inaccurate substitute for actual measurements of field strengths in the homes. Moreover, a potential bias was noted in their application of the wire coding system because it was not blind—the researchers doing the coding knew which homes were those of cancer victims.

When a similar study, conducted the following year in Rhode Island, found no evidence of links to cancer, many researchers dismissed the Wertheimer-Leeper findings.

Their work has surfaced again, however, in the wake of a second study of childhood cancer in Denver, completed in 1986 as part of the utility-funded New York State Power Lines Project. This study expanded on Wertheimer and Leeper's work and improved on some of the weaknesses in the original study's design. Conducted by David Savitz, now at the University of North Carolina, and Howard Wachtel and Frank Barnes of the University of Colorado, this investigation used a wire coding system similar to that developed by Wertheimer and Leeper but also used point measurements of magnetic fields in the subjects' homes. In this study the coding was blind, and it used a set of children entirely distinct from those in the Wertheimer and Leeper study. Like Wertheimer and Leeper, Savitz and Wachtel did find a modest statistical correlation between children with cancer and the proximity of their homes to high-current-configuration

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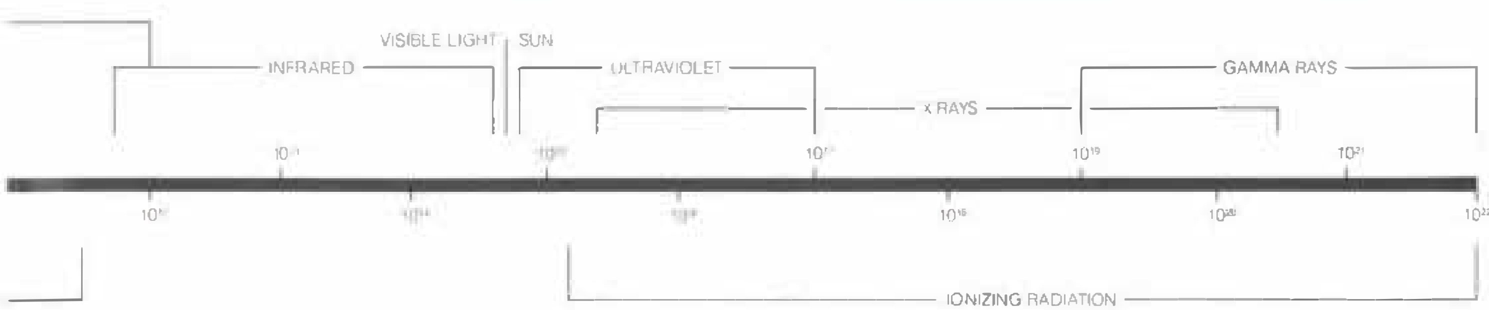


The Debate on Health Effects

Do electromagnetic fields from power lines and household appliances cause cancer? Researchers are struggling over how to interpret today's conflicting data and stepping up the pace of inquiry.

lines. However, the correlation between cancer and the measured magnetic field levels in the homes was weaker. In fact, the margin for error in the statistics suggests that there may be no correlation at all between cancer and the measured fields (graph, page 13).

"This finding is curious," says Leonard Sagan, who manages EPRI's field effects research. "If the magnetic fields are causing cancer, one would expect a pronounced correlation with the actual field measurements. But that isn't the case. Instead, the stronger correlation is with the pattern of power lines outside the homes. It is conceivable that wiring configuration is a better predictor of long-term exposure than point measurements of the magnetic field because the location of the wires stays the same over periods of years, while instantaneous field levels vary throughout the day. Another possible explanation, however, is that some other factor associated with the lines but having nothing to do with magnetic fields may be involved."

He suggests that a higher density of power lines and current flow is likely to be associated with more crowded, urbanized neighborhoods where there is more traffic, noise, air pollution, and exposure to hazardous chemicals. These areas might also contain older homes with pipe leaks that could lead to water contamination. Any one of these factors could conceivably contribute to cancer.

"The wire codes do seem to correlate with cancer, at least in the Denver area," says Howard Wachtel. "Our study and the Wertheimer and Leeper work have established that. But whether the cancer is caused by magnetic fields or by something else remains an open question.

"Our greatest problem is that we don't have any reliable characterization of how much field exposure these children received in the period before they contracted cancer. We're like archaeologists searching for some way to under-

Sources of Exposure

Exposure to electric and magnetic fields is an inevitable consequence of living in a society that uses electricity. The relative contribution of different sources to overall exposure is not well documented, but it appears that household and workplace appliances and equipment provide at least as much exposure as power lines. EPRI has several projects under way to measure and analyze public and occupational exposure patterns.

stand past conditions. Both the wire coding and spot measurements are imperfect indicators of what those conditions were."

Although they agree that the exposure measures have inherent weaknesses, Wachtel and Savitz place different interpretations on their study's results. Savitz maintains that a number of factors could be responsible for the cancer cases and that magnetic fields are high on that list of possible agents. Wachtel believes it more likely that some other agent that happens to correlate with the high-current-density power lines is the culprit.

The fact that these two co-workers interpret the evidence differently highlights the complexity and uncertainty that pervades this field. Paradoxically, the majority of the epidemiologic studies conducted to date suggest a weak association with cancer, and yet most scientists interpreting this body of work believe that the evidence is still too tenuous and fragmentary to draw any conclusions. Most investigators agree, however, that the findings are suggestive enough to deserve further inquiry.

"We're not talking about strong associations like those found with smoking and lung cancer," explains Sagan. "It's widely acknowledged that smoking increases the risk of lung cancer about 10-fold. With the field effects epidemiology on the other hand, we're seeing incomplete evidence for weak association. Savitz's numbers, for instance, suggest that there might be a little less than a doubling in the cancer incidence (from about 1 to about 2 in 10,000 per year) for children living near high-current-configuration lines. But the range of experimental error for these results also extends down to where there may be no increase in risk to this population."

Sagan maintains, however, that the patchiness of the evidence gathered to date does not imply that the early studies can be ignored. "This is how science proceeds," he says. "We start with fishing expeditions and focus our investigations as our understanding grows. Some important concerns have been raised by these early studies, but we have to recognize their limitations. And as we evaluate these and future studies we must remember that there are criteria that make the results of some epidemiologic studies more convincing and meaningful than others. For example, statistically strong association specific to a single disease is more compelling than slight increases in a broad spectrum of health effects. The association should be biologically plausible, and other potential causes, or confounding factors, should be accounted for. The findings are strengthened if they appear consistently in diverse populations and circumstances, particularly with some form of dose-response gradient."

Most of the epidemiologic studies conducted to date on electric and magnetic fields and human health have weaknesses in one or more of these criteria. The lack of good exposure data is a pervasive problem. Wire codes are inherently incomplete and imprecise indexes of actual exposure, and the kinds of point measurements made in the Savitz study are not necessarily good predictors of what field levels were in the past. Neither measure addresses the children's pattern of exposure as they experience different field intensities in their daily activities.

A number of occupational studies have relied on job titles alone as an indication of the exposure levels in various professions. This approach has obvious drawbacks as it clusters individuals who may in fact experience widely different exposures. Electrical engineers, for example, have been assumed in some studies to experience uniformly high exposure despite the fact that some of them work near equip-

Putting Fields Into Perspective

The electric and magnetic fields from alternating-current power lines and appliances oscillate with a frequency of 50 or 60 cycles per second (60 in the United States, much of the Americas, and western Japan). Both types of field have magnitude and direction. The electric field is measured in volts per meter (V/m) and the magnetic field in teslas (T). (Another unit commonly used to measure magnetic fields is the gauss, which equals one ten-thousandth of a tesla.)

Although most of the health effects concern has centered on fields generated by power lines, many people may receive more exposure from indoor wiring and appliances in the home or workplace. Field exposure is thus an inevitable consequence of living in a society that uses electricity.

Natural background levels for electric fields are less than 0.001 V/m, those near distribution lines range from 0.1 to 1 V/m, typical levels in homes and workplaces are 1–10 V/m, fields within one foot of small appliances reach 20–200 V/m, and the field strength right next to an electric blanket approaches 10,000 V/m (10 kV/m), which is about the maximum level a person experiences standing on the ground directly beneath a 765-kV transmission line, the highest voltage now used for power transmission.

Because fields weaken rapidly with distance from their source, those produced by power lines are strongest right under the conductors, and they

Continued on page 15

EPRI Field Effects Research

EPRI is sponsoring extensive research in a number of areas to improve exposure assessment and explore the occurrence and mechanisms of effects in animals and cells. Insights from these areas will strengthen the epidemiology and enable researchers to resolve questions raised about health effects in humans.

EPIDEMIOLOGY

Residential Studies Some epidemiologic studies focusing on home environments have suggested a positive association between magnetic field exposure and cancer, particularly in children. Other studies have found no such link. Most scientists believe that the evidence falls far short of proving a health risk because the associations being reported are relatively weak and because many of the studies suffer from limitations in methodology, such as a lack of exposure data and a failure to account for the potential influence of other carcinogens. To clarify these uncertainties, EPRI has launched a study of childhood cancer that will examine a number of potential agents, including magnetic fields.

Occupational Studies The research on workers assumed to be exposed in their jobs to high electric and magnetic field levels is fairly limited and shows inconsistent results, with some studies reporting elevated cancer rates in electrical professions and others finding no effects. Most of these studies also suffer from poor exposure characterization and fail to account for factors other than fields that could contribute to disease (like the metal fumes that welders and electricians often breathe). EPRI is supporting a study of leukemia among telephone company employees to determine if there is any increased risk among phone linemen as a result of exposure to fields from power lines. The Institute is also starting a similar study of utility employees.

EXPOSURE ASSESSMENT

EPRI has developed a portable monitor called EMDEX and a wristwatch-style dosimeter to gather detailed data on the exposure of individuals to electric and magnetic fields. This information will alleviate weaknesses in earlier research caused by incomplete exposure assessment. EPRI's EXPOCALC software package is already used by more than 100 utilities for estimating human exposure to electric fields near transmission lines; a second version that will also measure magnetic fields will soon be available.

BASIC SCIENCE

A decade of animal research has shown that in certain instances electric and magnetic fields can have subtle but measurable effects on such areas as behavior, cellular membrane function, and biologic rhythms. No studies have found that these effects are pronounced enough to lead to disease, however. EPRI is funding a number of laboratory studies to help unravel mechanisms of these effects, as well as a project to explore whether magnetic fields cause cancer in animals. The results will help scientists evaluate the biologic plausibility of the epidemiologic findings suggesting that magnetic fields may promote cancer in humans.

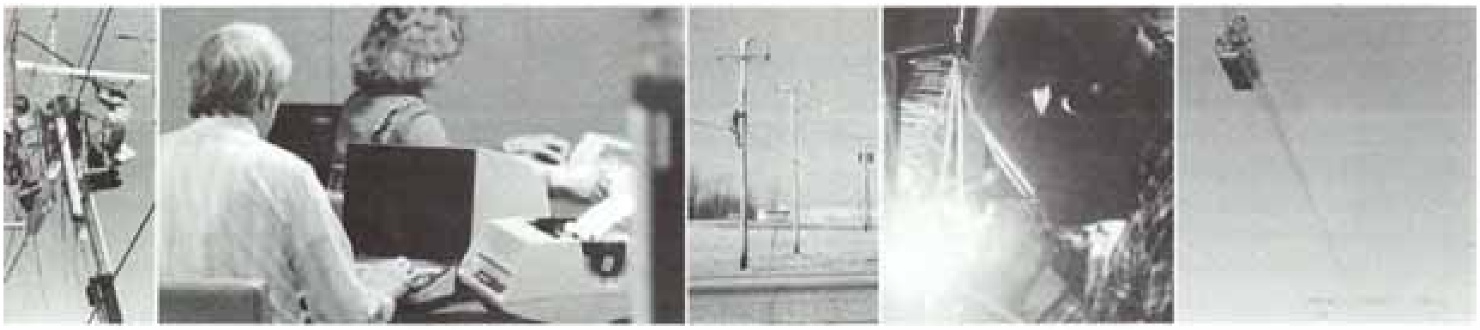
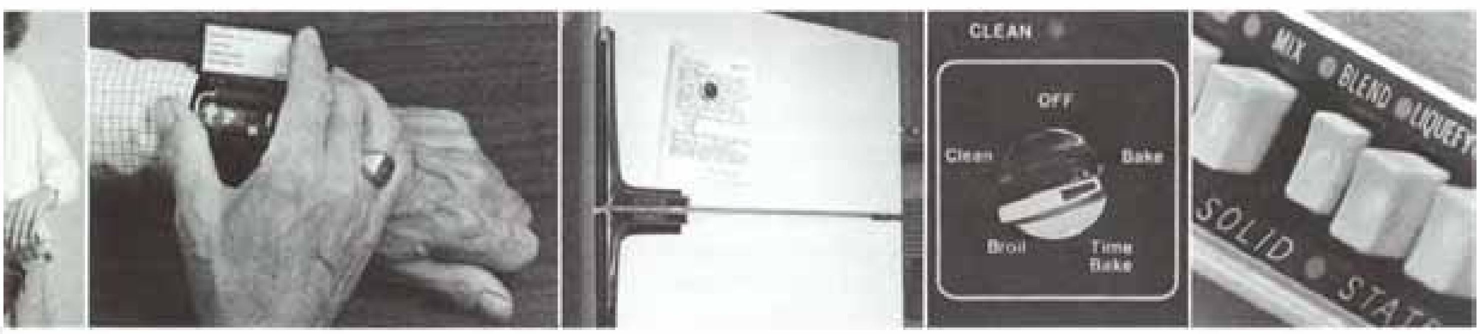
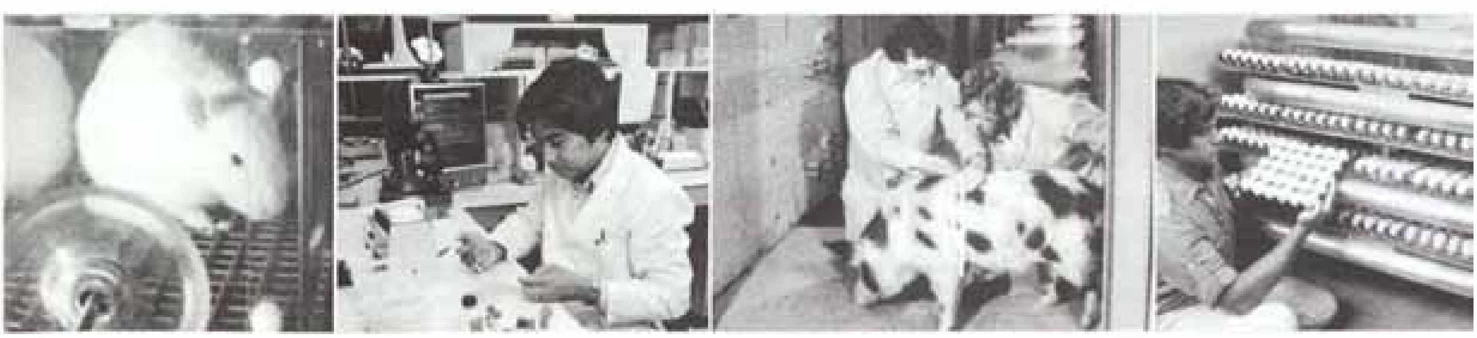


Photo courtesy Hydro Quebec





ment that produces strong fields, while others work in offices far from such equipment.

Savitz and Calle surveyed the epidemiology on workers in so-called electrical occupations, such as electricians, linemen, and motion picture projectionists. Overall, the research in this area suggests that these professions have a slightly elevated risk of leukemia and brain cancer.

"The big question," says Savitz, "is what the source of that risk is. Maybe it's electric or magnetic fields or maybe it's something else. There may be some sort of sociologic process by which certain types of people with different baseline cancer risks select certain kinds of careers. And there are many other workplace exposures, like chemical solvents, that could be responsible. In fact, because these studies are based on job titles rather than on exposure data, we really don't know if the individuals with cancer have been exposed to elevated field levels. The whole issue is worth pursuing because whatever the cause of the apparent elevated cancer incidence in these job categories, it's worth knowing about."

He cautions that although the lack of exposure data weakens the epidemiologic findings, this flaw alone cannot negate evidence in favor of an association. "In fact," he says, "such imprecision should tend to weaken an association rather than produce spurious positive associations." In other words, if there is a true effect, poor exposure data would tend to mask, rather than accentuate, the association.

Savitz maintains that very little can be concluded from the existing findings in either the public or occupational areas. "Using standard levels for scientific proof, the argument that these fields cause cancer, reproductive damage, or other health effects falls far short of convincing. From the perspective of public health protection, however, one might ask whether the suggestions of health effects raised in some studies have been convincingly negated by superior research. The answer is that they clearly have not. The social and political choices relating to this issue fall outside the bounds of science, but there is a major role for further epidemiologic study in providing the basis for those decisions. Specifically, more research will either bolster the case that these exposures cause health damage or alleviate the concerns raised in past studies."

Ongoing and future work

Because the federal government has reduced its work in the broad area of electric and magnetic fields and the New York State–managed research has been completed, EPRI and the utility industry are the major remaining sponsors of field effects research. EPRI has spent $15 million on such research over the past decade and has recently increased its support from about $2 million to at least $3 million annually, with additional increases planned for the future.

Much of the early work investigated whether high-voltage electric fields produce biologic effects in plants and animals. The focus then was on electric fields from transmission lines because a number of such lines were being contested, in part, on the grounds of health concerns. Those studies demonstrated that effects do occur but do not appear to be harmful. With this groundwork established, EPRI's research emphasis is now moving to address concerns of a link between cancer and magnetic fields from residential exposure (including that from neighborhood distribution lines) or from occupational exposure. The program has shifted to emphasize epidemiology, exposure measurement, and in a new effort, cellular-level and whole-animal research aimed at elucidating any mechanisms of interaction

Concern about electromagnetic field effects began in this country during hearings begun in 1974 to address a proposal by New York State utilities to build two 765-kV transmission lines. The health concerns were suggested by reports reaching the West of Soviet studies done a decade earlier on workers in transmission switchyards who had complained of appetite loss, fatigue, headaches, insomnia, and reduced sexual drive. The Soviet research proved to have a number of flaws, but it did much to fuel the field effects controversy.

After hearing 31 expert witnesses present more than 14,000 pages of testimony over a period of four years, in 1978 the commission judges in New York concluded that although occasional exposure to the fields from extra-high voltage lines did not pose a hazard to human health, there were too many inferences of possible risk from continuous or long-term repeated exposure for them to responsibly ignore. To resolve some of the uncertainties they instituted a $5 million research program called the New York State Power Lines Project (NYSPLP) to be paid for by the state's utilities and implemented by an independent scientific advisory panel.

The commission approved construction of the power lines but mandated that they be built with corridors

Evolution of an Issue

wide enough to ensure that the field intensities at the edges of the right-of-way were no greater than 1.6 kV/m, a level that was typical for existing 345-kV lines in New York. "In effect," says Daniel Driscoll of the New York State Department of Public Service, "the commission declared a moratorium on higher fields until the results of NYSPLP could be evaluated." The scientific panel's final report was released last July. It called for more research but concluded that the findings to date "do not readily translate into concrete regulatory recommendations on width of right-of-way, line heights, or location of lines near homes."

The process in New York was fairly orderly compared with the emotional response in Minnesota, where opponents of a direct-current transmission line being built from North Dakota to Minneapolis engaged in acts of vandalism that ultimately caused $9 million in damage and security expense. The line was completed in 1978, but this did not put an end to the climate of concern that had arisen during construction.

Complaints of health problems from residents living near the line prompted the Minnesota Environmental Quality Board to appoint an independent science advisory panel to study the issue and make recommendations. In its final report issued in late 1982, the panel concluded, "There is now no scientific basis to believe that the electric and magnetic fields and air ions produced by the . . . power line pose a hazard to human or animal health."

The same group of experts was reconvened in 1985 to revisit the issue in light of new scientific evidence. They reached the same conclusion as in their earlier report, effectively ending the controversy in Minnesota.

Laying the issue to rest in one state may mean little in other settings, however, as Houston Lighting & Power learned in a 1985 trial against the Klein (Texas) Independent School District. The trial grew out of the school district's opposition to the utility's construction of a 345-kV transmission line across the district's property. The district agreed that the utility had followed all standard legal procedures in obtaining the right-of-way but alleged that HL&P had "grossly abused its discretion" by building the line near their schools, thereby allegedly presenting a potential health risk from the fields produced by the line.

The jury listened to six expert witnesses (four brought by the school district and two by the utility) testify on the possible health effects of fields from 345-kV lines. The jury was never asked to decide on the question of whether fields from the transmission line do, in fact, pose a health hazard.

Despite the fact that the jury never determined that the utility had placed anyone at risk by building the line, it ruled that HL&P had "abused its discretion" in building the transmission line near the district's schools. The jury awarded the school district $104,000 plus interest in actual damages and $25 million in punitive damages, and the court ordered HL&P to restrict use of the line to emergencies outside of school hours pending appeal of the case.

As of mid August, the case was still in the courts, and the line—a major conduit for power flow between Houston and Dallas—had essentially been shut down for almost two years. HL&P has solved the power flow part of its problem in the interim by building a 2.5-mile reroute around the school property, enabling it to use the line again while the legal battles continue.

As the HL&P case reveals, the field effects issue is far from being resolved. Investigators have not yet been able to satisfactorily address the key uncertainties, and the legal debates continue in the absence of sound scientific evidence. But if answers are to be found, they will come from science, and that is where EPRI and other supporters of research in this area can play a critical role. □

between fields and living organisms.

Researchers at Johns Hopkins University are working on an EPRI-funded study to examine the risk of acute leukemia from magnetic field exposure in telephone industry employees. The telephone industry was chosen because before divestiture it had a centralized data base on one and a half million workers and because some of those employees, notably linemen, are exposed during the course of their maintenance work to electric and magnetic fields from power lines. The project is scheduled for completion in 1988.

The Institute recently launched a similar epidemiologic study of utility company employees to determine if the incidence of leukemia and brain cancer is higher among linemen, electricians, and others who receive high exposures. That work is just getting under way.

On the public health front, EPRI has contracted with the University of Southern California to conduct a comprehensive epidemiologic study of childhood leukemia. "One of the main criticisms of other published studies of this type is that not enough attention was paid to other variables that might have influenced the development of cancer or leukemia," comments Robert Black, who manages epidemiologic research in EPRI's field effects studies. "This study will be one of the first in which careful attention will be paid to other factors that might be responsible for disease."

To fill a critical gap in the research, EPRI is planning a study to determine whether magnetic fields promote cancer in laboratory animals. If they do not promote cancer, that is valuable knowledge. If they do promote cancer in certain animals, then important questions on dose can be examined. Is long-term, low-level exposure of concern or are short-term spikes in exposure implicated? Are the effects related to specific field frequencies? The fact that no such study has yet been conducted hampers scientists' ability to evaluate the biologic plausibility of the epidemiology on magnetic fields and cancer.

EPRI also plans to fund several new studies on the mechanisms of interaction between organisms and electric and magnetic fields. "We're trying to achieve a basic understanding of how these fields affect biologic materials at the cellular, membrane, and macromolecular levels and to relate these mechanisms to possible disease processes in whole animals," explains Project Manager Charles Rafferty.

EPRI's program is also addressing the weaknesses in exposure measurement that have plagued so much of the early field effects research. A new instrument developed by EPRI measures both electric and magnetic field exposure with greater ease and accuracy than did any earlier monitors. Called EMDEX (electric and magnetic field digital exposure), this device samples and records field levels over extended periods and provides data on how exposure varies over time.

According to EPRI Project Manager Stan Sussman, "The exposure monitors available until now were either too bulky for measuring the exposure of people moving around in the course of a day or too basic to provide much useful information. What we need is a portable, lightweight device that will gather a lot of data." EMDEX fits the bill. Measuring 6 × 4 × 1½ inches and weighing in at less than a pound, EMDEX can be worn in a belt pouch. Powered by one 9-volt battery, the device measures magnetic fields in three axes, motion in the geomagnetic field, and electric fields—all of these up to 10 times a second. The data are stored in an on-board microprocessor and downloaded periodically to a personal computer for analysis. The monitor is equipped with an event indicator button that the user can push for identifying specific events in the measurement record. Ten prototypes have been built and calibrated, and EPRI hopes to have 100 of them in use by the end of this year.

One of the first applications will come in a study to measure field exposure in a range of occupations, some of which are associated statistically with a higher risk of leukemia. "This is a very ambitious study," Sussman explains. "We'll be assessing the exposure of 1000 workers in Los Angeles, Washington State, and New Zealand." These locations were chosen because epidemiologic studies conducted there found slightly elevated leukemia rates among electrical workers. None of the studies, however, involved any actual measurements of field exposure. Half of the workers studied will come from electrical occupations and half will not. The sample will include workers from government offices and from the aircraft, utility, and aluminum industries.

"We hope that these measurements will allow us to design better epidemiologic studies," says Sussman. "The job categories that have been used in the past are too aggregated. They need to be broken down by particular task and exposure." Welders, for instance, are lumped together in these studies, even though the exposure of those using electric arc equipment will be much different from that of those using flame welding equipment. "This study and others like it will remove a lot of guesswork," Sussman observes. "We'll finally begin to know which jobs and which particular tasks really do involve high exposure."

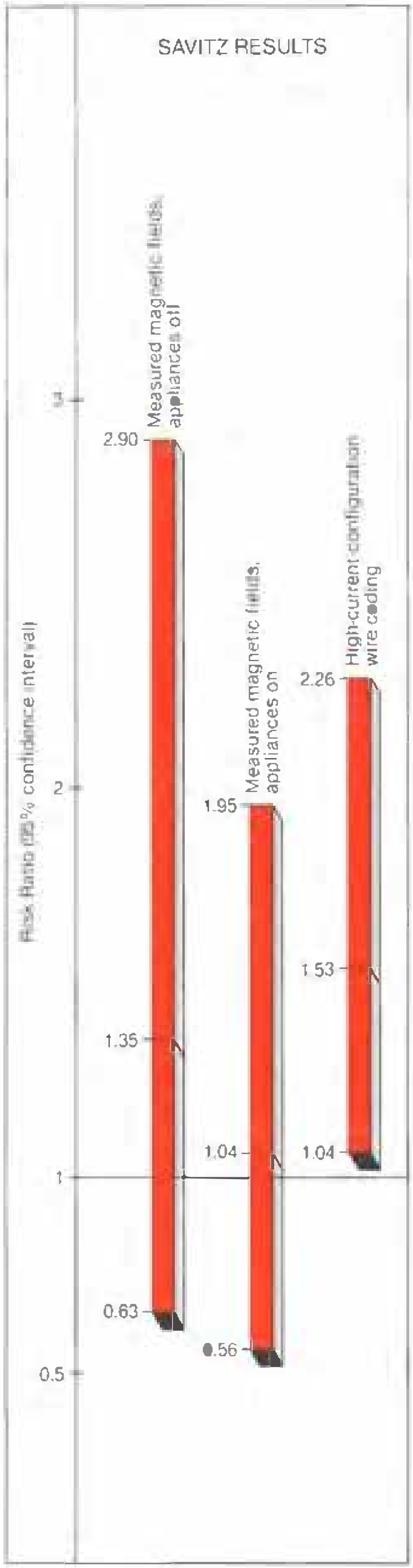
In a related effort, EPRI is supporting development of a wristwatch-style dosimeter that will operate much like household pollution monitors or the badges worn by employees at nuclear power plants. The dosimeter will measure cumulative exposure. Although it won't gather as much information as EMDEX, the wristwatch meter will be very useful for gathering data on large numbers of people.

Another exposure assessment tool to emerge recently from EPRI is a computer program called EXPOCALC. The first version is already used by more than 100 utilities for estimating human exposure to electric fields near transmission lines. Work is nearly complete on a second version, which will assess magnetic field exposures as well. The user enters data on line voltage, current flow, height, sag, configuration, ambient temperature, nearby obstructions, and other relevant parameters. EXPOCALC will be especially valuable for utilities developing environmental reports on proposed transmission lines, for comparing field and laboratory study results, and for assessing exposure and risk.

These field measurement efforts conducted by EPRI's Environment Division are aimed principally at characterizing human exposure. A complementary effort just getting under way in the Electrical Systems Division will focus on refining the electrical engineering needed to measure fields more accurately and to identify their sources. "It's easy to identify and predict the source of a magnetic field if you are standing right under a high-voltage line," explains James Mitsche, a project manager in the Electrical Systems Division. "It's not so easy with the fields inside a home or workplace. There, many sources are involved, including appliances, lights, indoor wiring, power lines, and ground currents. We hope to develop techniques that will allow us to measure and predict the relative contribution of all such sources."

Advisory panel

These projects reflect the types of work the Institute is pursuing. To ensure that these efforts are well designed and appropriately directed, EPRI has asked 15 independent scientists and industry experts to serve on a field effects over-



Cancer Link Far From Certain

The results of epidemiologic studies are often expressed in terms of risk ratios, with values greater than 1 suggesting elevated risk in the exposed population. Because they are based on data from a limited number of subjects, such risk ratios are only estimates of the true risk, which may fall (with 95% probability) anywhere within the confidence intervals shown. The wider the confidence interval, the less precise the risk estimate. Moreover, if the lower bound of the confidence interval dips below 1, it is not possible to reject the hypothesis that the true risk ratio is 1, meaning that there is no added risk for the exposed group. Savitz and his colleagues found an association between cancer and homes near high-current-configuration power lines (1.53 estimated risk ratio). When the researchers measured magnetic fields directly, however, they obtained quite different results. Measurements made with appliances turned on suggested no association with cancer (estimated risk ratio 1.04). Measurements made with appliances turned off yielded a risk ratio of 1.35. Researchers disagree as to whether or not this suggests an association. The fact that the confidence interval falls below 1, however, means that the data do not rule out the possibility that there is no association. These and other results from the Savitz study thus raise important questions that deserve further inquiry, but fall short of proving a link between magnetic fields and cancer.

sight committee. Because of the breadth of subject matter, the group is divided into subcommittees on epidemiology, exposure assessment, and basic science. The subcommittees will meet several times a year to monitor ongoing research, review research proposals, and make recommendations on future work.

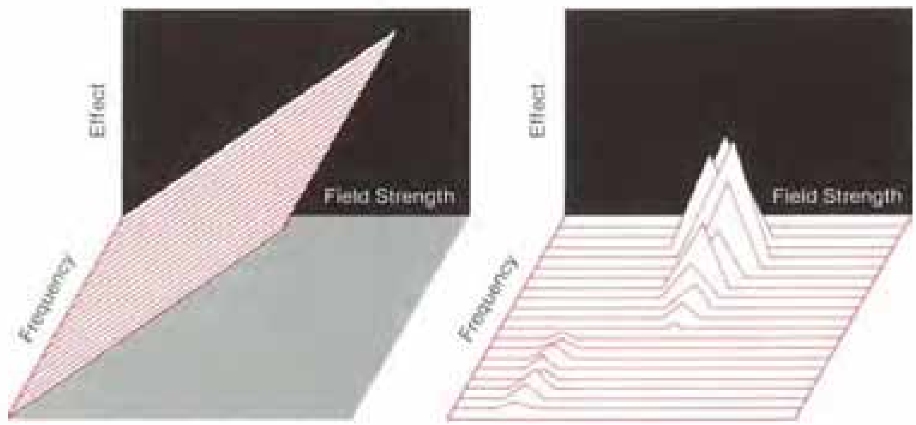
The full committee is chaired by Gilbert Ommen, dean of the School of Public Health at the University of Washington. "EPRI has shown unusual leadership in building and supporting a research agenda on the effects of electric and magnetic fields," states Ommen. "This is particularly noteworthy in view of the government's cutbacks in this area. Much more needs to be learned in order to interpret the rather uncertain findings that have been gathered to date. Our panel is committed to providing objective, external advice and guidance to EPRI in this important area of research."

The work continues and firm answers are elusive. The evidence for an association with cancer or any other disease is tenuous, but legitimate questions do remain. Leonard Sagan observes, "Although there is no scientific consensus in this area and the results linking magnetic fields to adverse health effects are weak, the fact that reputable studies even suggest that such a link exists places a responsibility on EPRI and the industry to reduce the uncertainty and to put any risks that may exist into perspective."

But uncertain risk is a difficult matter for society to deal with. Should individuals and communities do anything in the meantime to protect themselves? Should they erect shielding around power lines or stop using electricity? "Probably not," says Savitz. "There is so much uncertainty that it doesn't seem wise for individuals or society at large to expend a lot of resources to avoid a danger that may not exist. If there was a little 59¢ device that would eliminate exposure it would be worth

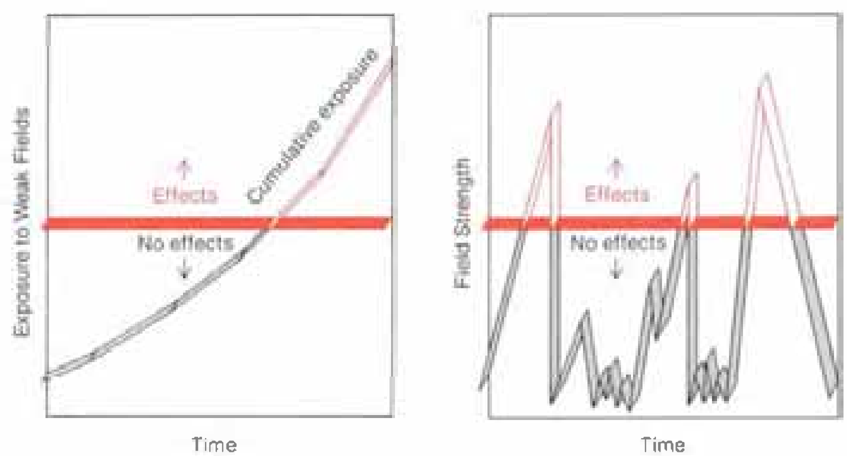
Two Key Uncertainties

Researchers are grappling with a number of unanswered questions in their study of electric and magnetic fields. Two of these are highlighted below.



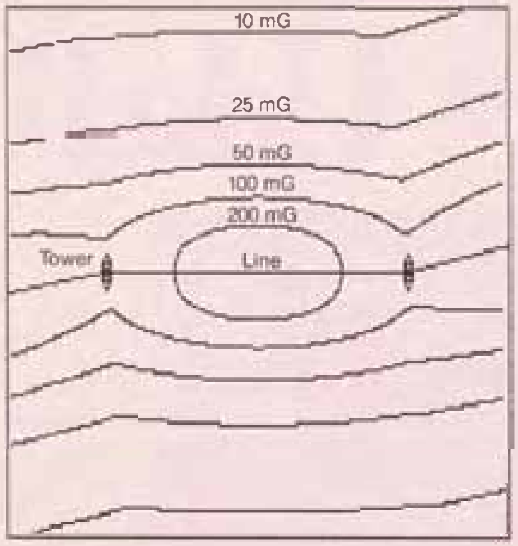
Field strength → effect? Field strength + frequency → effect?

1 Do effects increase linearly with field strength, independent of radiation frequency, or, as some studies indicate, are biologic systems particularly sensitive to certain windows of frequency or to particular combinations of field strength and frequency?



Cumulative low-level exposure → effect? Brief high-level exposure → effect?

2 If an effect exists, is it more likely to result from chronic exposure to low-level fields or from brief exposure to strong fields?



Continued from page 7

fall off sharply to either side. An electric field with a maximum strength of 10 kV/m at head level beneath a line will diminish to less than 0.5 kV/m 60 meters away. Electric fields are easily blocked by vegetation, buildings, fences, and other objects. They can also be virtually eliminated by grounded shield wires or screens in direct contact with the earth. Buried power lines produce almost no electric fields above ground.

Magnetic fields are also ubiquitous, as anyone who has used a navigational compass knows. The earth's direct-current field is about half a gauss, with an alternating 60-cycle-per-second (Hz) component of about a billionth (10^{-9}) of a gauss. The maximum 60-Hz magnetic field value beneath a distribution line is several hundredths of a gauss and that beneath a 765-kV transmission line is about 1 gauss. Typical levels in homes fall in the range of 0.1 to 50 milligauss, and the values within several inches of appliances like televisions, kitchen ranges, and hair dryers can be 10 to 20 times higher. Unlike electric fields, magnetic fields easily pass through most objects, including buildings, earth, and people.

In addition to field strength or intensity, the frequency (number of cycles per second) may be an important determinant of biologic effects. A few studies have suggested that effects are more pronounced in certain frequency windows or bands. "There might be critical frequency windows," explains EPRI's Charles Rafferty, "as well as thresholds in the biologic influence of field intensities, below which no effects occur. Or perhaps there is more of a linear relationship so that stronger fields imply greater effects. This is only one of the exposure uncertainties we are grappling with. Should we be concerned with just magnetic fields, both electric and magnetic fields, or neither one? Is low-level chronic exposure more significant than acute exposure to higher fields? Nobody knows because not enough experiments have been conducted. These are questions that require investigation." □

it, but in reality there is so much uncertainty and the costs of reducing exposure are so high that it is difficult to justify such expenditures."

M. Granger Morgan of Carnegie-Mellon University has studied the options for policy responses under the climate of uncertainty that pervades the field effects issue. He identifies possible actions ranging from pregnant women avoiding the use of electric blankets "just in case" to efforts by utilities to design and site future power lines in ways that minimize public exposure to fields. He points out, however, that "rational decisions in the face of uncertainty offer no assurance of good outcomes. For that, one needs certainty. Thus, the best policy in this area is to concentrate on increasing our understanding of the science of power frequency field effects." That's exactly what EPRI is doing. ■

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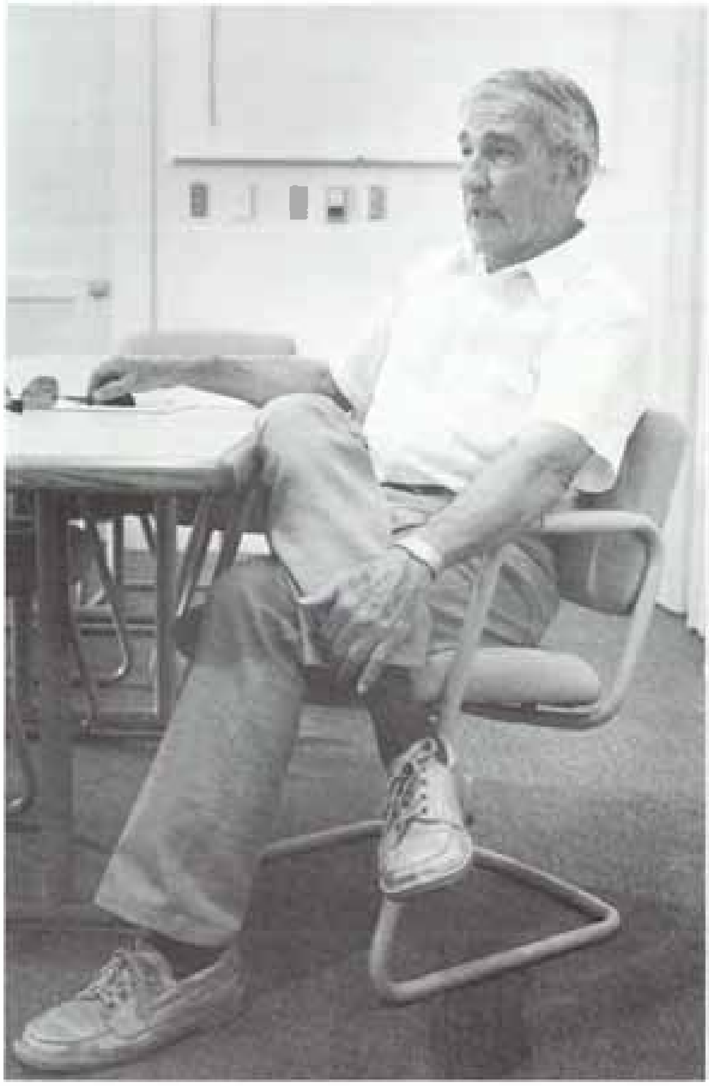
This article was written by Michael Shepard. Technical background information was provided by Leonard Sagan, Robert Black, Stanley Sussman, and Charles Rafferty, Environment Division.

Stewart Udall



Conservationist by Heritage

A former secretary of the interior, Udall has kept sound use of natural resources front and center as a planner, author, advocate, consultant, and now, member of EPRI's Advisory Council.

From his accomplishments as a two-term secretary of the interior in the sixties, Stewart Udall is clearly a conservationist. From his even earlier record as a three-term congressman from Arizona, he is a politician. But from his life then and since, Udall prefers to think of himself as an environmentalist and public servant. The distinctions become clear in the attitudes he expresses and the traditions that motivate him.

One of those traditions is the heritage of Arizona, his birthplace, his home, and always his fascination. Later this year Udall will remind us that he is also an author—and now a historian—with publication of *To the Inland Empire: Coronado and Our Spanish Legacy*, an interpretation of Spanish exploration and settlement in the American Southwest. "I worked on the book for four and a half or five years," he says. "It was a lot of fun because it's part of my life. I grew up along the Coronado Trail, over by the New Mexico border.

"The history of what is now the United States, the history of European contact, began here," Udall adds emphatically, "and people in the East don't know it!"

Udall built on his southwestern origins with career work in law, politics, conservation, environmental and power planning, industrial consulting and mediation, writing, and now, advice to EPRI's Board and management. For over a year he has been a member of EPRI's Advisory Council, 20 or more invited professional men and women who bring the insights of their professional lives and constituencies to bear on EPRI's research program. In the course of their individual and collective exchanges with EPRI's directors and staff, some of the directions and dimensions of new electric power technology are subtly shaped for a better fit with the overall needs of our society.

From farm to Cabinet

The formative part of Udall's life centered in the Arizona town of St. Johns, settled by Spanish wagoneers but later having a Mormon community founded by Udall's grandfather. St. Johns included those two traditions, not always compatible, Udall admits, plus his grandfather's "little dinky $2000 hydroelectric turbine" that brought in electricity only a few years before Udall's birth in 1920, the family's alfalfa and cattle interests, and his father's role as a county judge.

"I come from a generation that experienced electricity as a turning point," Udall reflects. "I have a long view of electric power and what it does to people's lives.

"I'm a farm boy," Udall goes on, "and I also rode with the cowboys when I was 11 or 12. I think it's a great way to grow up; it makes me kind of old-fashioned, very conservative in some ways."

But the county judge was a powerful model, and Udall and his two brothers became lawyers. Two other forces also moved him from St. Johns in a way that might not have been decisive a generation earlier. First, after a period in college he traveled and worked for two years in New York and Pennsylvania as a Mormon (Latter-Day Saints) missionary. Second, he joined the Army Air Force and was a bomber gunner in Europe during World War II.

By 1948, when Udall graduated in law from the University of Arizona, his father had been elected to Arizona's supreme court, and Udall recalls, "He encouraged us to get into politics; he called it public service." During his own first six years of practice, Udall wasn't elected to anything, but he was appointed to a three-year school board term, and he managed what turned out to be losing campaigns for three Democratic gubernatorial candidates.

Adopting the view that when all you have are lemons, you make lemonade, Udall turned the circumstance to his advantage. "I got to understand politics," he says. "I became a participant. I served my apprenticeship. And when, much to our surprise, our congressman quit, I said 'That's for me,' and I ran for his seat in 1954."

Udall won handily then and three more times. But his mark on U.S. public service (and its mark on him) is from his eight years as secretary of the interior for presidents John Kennedy and Lyndon Johnson. Like many career events, the Cabinet appointment had a fortuitous twist. "I hadn't known Kennedy," Udall recalls, "and what we later called charisma I called Hollywood. I was skeptical of it. But we were thrown together. I was on the Education and Labor Committee and was Senator [John] Kennedy's counterpart in hammering out labor reform legislation.

"It was very controversial; because of Hoffa and the teamsters, there was the feeling that a lot of labor excesses and abuses had to be curbed. So I got to see Kennedy at work in an intimate way. We tested each other and we liked each other."

Udall went on to work for Kennedy's campaign, delivering the vote of Arizona's delegation at the 1960 Democratic presidential convention. But Kennedy didn't carry Arizona in the election. "He had a big ballot margin when he hit the Mississippi River, but he almost lost—he carried only two western states."

His own appointment as secretary of the interior draws a politician's reality from Udall. "Kennedy didn't know anybody in the West much, but he liked me. I think I earned the appointment because I helped him at a crucial time." Then a sense of the personal and regional honor creeps in. "I was the first person from Arizona to go into the president's Cabinet. That was a great experience."

The shift to environmentalism

Udall's interest in conservation is tangible in the record of his years as secretary of the interior. "It was a kind of golden age for parks, I think, an explosive expansion of outdoor recreation not equaled before or since." The numbers are impressive: 4 new national parks, 6 new national monuments, 8 seashores and lakeshores, 9 recreation areas, 20 historic sites, and 56 wildlife refuges.

It was also the period of the Wilderness Bill, the Wild and Scenic Rivers Act, the National Trails System Act, and the National Historic Preservation Act. Udall's administration implemented a Columbia River treaty with Canada, withdrew an unprecedented expanse of Alaskan lands from development, established the Land and Water Conservation Fund, and founded the Bureau of Outdoor Recreation.

Secretary Udall was by turns researcher, planner, and lobbyist Udall, and at times he was also inspector and vacationer Udall. "There were summer trips to investigate new parks, and I would take the family along. We'd just camp out. Our favorite park is one that I had a hand in getting established—Canyonlands, in Utah."

The family outdoor tradition continues today, as Udall and his wife bring their three grandchildren into the campfire circle. And the family is still close-knit, as it was when Stewart Udall and Ermalee Webb met (his cousin having married her sister) and were married while they were in college 40 years ago. But his family ties are hardly stronger or more conscious than his ties to the rest of nature.

Udall the farm boy remembers St. Johns, the felt connection with the soil and the sense of stewardship toward it. "That is something I believe in," he says thoughtfully. "I grew up in barren country—juniper, piñon, the high plateau—so even with a little dam and irrigation, we learned the importance of water. There's a tie to the land. And there wasn't a long growing season. When you had a late frost, you lost your fruit crop. That was something you lived with. When people ask me how I became a conservationist, I tell them I grew up that way."

But a larger context of environmentalism came to embrace Udall's sense of the ecological web of which we're a part. "Like all sociopolitical things, it evolved. And in my view it began with Rachel Carson and her book *The Silent Spring* in 1962. She had worked for the Department of the Interior at one time," he adds before continuing to explain.

"We began to see that conservation had to be broadened, that if you weren't concerned with side effects and the total environment, then you weren't really a good conservationist. If you weren't concerned about pesticides, then the birds you were supposed to protect would be destroyed. That link was very dramatic to me. That was the message of Carson's book, and I think that environmentalism began to evolve early in the 1960s. It came to a culmination in the 1970s, and it's now a permanent part of our mental furniture."

By definition, at least, environmentalism takes the well-being of our natural surroundings out of the hands of conservationists and gives it to society. So, how are we doing? Intellectual acceptance is still running well ahead of performance, for the most part. But as Udall thinks of his own experience with the electric power industry, he sees a difference.

"In my view, 90% of the utility executives recognize that they're not fighting environmental concern anymore. They're trying to understand it, to work with it, to hammer out compromises so that they can do what they have to do in a way that will be respected as environmentally sound. I mean, the difference between now and 25 years ago is dramatic."

This isn't to say that Udall's Department of the Interior contacts with electric power and other industrial interests were adversary. "I was in the power business myself; I was responsible for all the hydroelectric power generated by federal govermnment facilities."

From planner to advocate

Udall especially remembers two pioneering power projects in which his administration had a major role. "One was the Pacific Northwest–Southwest Intertie, which included this country's first large direct-current transmission link. We put that together, using federal resources and resources from private industry—mainly Los Angeles Water & Power, Pacific Gas and Electric, and Southern California Edison, but also Pacific Power & Light.

"It was a struggle," he recalls, "and I was right in the middle. It required compromise, but we did it. And when the oil embargo hit, the project paid for itself in two years."

Udall's other innovative accomplishment with electric utilities was a coal slurry pipeline that brings fuel some 275 miles across northern Arizona from Indian lands near Kayenta to a power plant operated by Southern California Edison in the narrow tip of Nevada, just west of Davis Dam. Udall's summary is succinct. "Edison got together with the Navajos for Black Mesa coal, and we put it together."

The transaction stands out because, he says, "The line had to cross the Santa Fe railroad tracks at several points. Santa Fe could have blocked it, but we talked them out of it. That was 20 years ago. The line is still in use today—the only such line anywhere in the United States. Congress later wrestled with similar proposals for 15 years and finally turned away. We did it."

The two government-industry transactions exemplify Udall's bridge between his principles and his workaday pragmatism. "There was strong cleavage between public power and private power in the 1960s. By party and by conviction, I was on the side of public power, and that meant it was difficult to bring people together. I think it was my pragmatism—coming from politics, from Congress, you know—that enabled me to work out things like the intertie.

"I didn't approach it ideologically, for which I was criticized by some," Udall admits. "I approached it with the view that we wanted to get things done, and if

"I think the Advisory Council is recognized as a kind of beacon, throwing light into the future so that the Board of Directors can pick the right direction with the right policies."

we had to make ourselves work together, we'd do that!"

Udall's bridge of candor and purpose has remained sturdy and well-traveled. It carried his message during a year as a visiting professor (environmental humanism) at the Yale School of Forestry, it brought readers to his syndicated column ("Udall on the Environment") in 1970, and it reinforced the objectivity of an environmental planning practice (The Overview Group) that he organized and led for four years at the turn of the 1970s.

Distinctions between public service, missionary work, and education aren't clear in Udall's professional purpose since his Department of the Interior days. Along with planning, he did a lot of lecturing, usually on the environment, he says, "but when OPEC and the energy crisis came along, they were my topics for several years." He managed his brother's unsuccessful presidential campaign in 1975 and 1976, "but when that ended up in a heap, with me at the bottom, I decided I'd better go back to law practice full time."

At first it was resource law, but in 1978 he joined legal teams on two class action personal injury suits, and a year later these took him back to Arizona. "I'm the lead lawyer against the federal government on behalf of a group of Navajo Indians who were some of the earliest uranium miners in the country. I'm also on a team representing individuals who lived in little Nevada and Utah towns during the days of atmospheric atomic bomb tests that produced fallout. They call themselves the down-winders."

From advocate to adviser

Udall's public and private careers have alternatively thrown him against many sides of many complex issues. They have put him in demand for consultive, mediative, and advisory roles. Today, he says, "I'm spending most of my time getting *off* boards." But one of the few that still engages him is EPRI's Advisory Council, which he joined nearly two years ago.

Again, Southern California Edison is a link, Udall having recently been a policy consultant to Howard Allen, now the utility's chairman, whom he met over the pipeline and intertie negotiations 20 years ago. "Howard thought I could make a contribution and urged me to accept EPRI's invitation. I said yes because of my long-term interest in electric power. I'm an old-timer; I've taken part in a very interesting period of a very vital industry. I think this industry has done remarkably well in adapting to the new environmental constraints of the past decade, and I wanted to help it continue to move forward effectively."

Even so, he admits he carried questions into his first Advisory Council meeting. "What's this all about? Is it a real working council?" He was immediately at ease, he says, and the words *vigorous, honest, straightforward,* and *industrious* all fall into his short, emphatic characterization.

Moreover, Udall is convinced that the Advisory Council is wanted and heard. "The moment I feel nobody is listening, I'll just quietly submit my resignation. But we bring nonindustry views, diversity; we even have pretty good arguments sometimes, and I think we're recognized as a kind of beacon, throwing light into the future so that the Board of Directors can pick the right direction with the right policies. You know, they even let the Council get into budget priorities. 'Are we spending enough in this area or that?'"

Udall's upbeat observations about his Advisory Council service typify his response to most matters. He isn't a Pollyanna, but he is positive. He accepts what hasn't been done; he doesn't waste energy lamenting it. Even more important, he affirms what can be done and especially what is done.

Much of Udall's perception of electric utility issues in recent years has been shaped by his service as a director of the Institute for Resource Management (IRM), a nonprofit foundation created by film star Robert Redford and others in 1982. IRM addresses the balance between use and preservation of natural resources by educating business, government, and environmental leaders, encouraging them to collaborate in solving important resource problems.

Twice, in 1983 and 1984, Udall has organized and led IRM symposia that focused on the power industry and its problems over fuels, technological and institutional changes, and the consequent risks and uncertainties. More diverse in makeup than EPRI's own annual Advisory Council seminars, the IRM symposia embraced utility heads, such as Allen of Southern California Edison, Freeman of TVA, Geist of New Mexico Public Service, and Shackelford of PG&E, and industry watchdogs, such as economist Charles Komanoff and physicist Amory Lovins, as well as regulators, association executives, academics, environmentalists, and a sprinkling of federal, state, and local government officials, both elected and appointed.

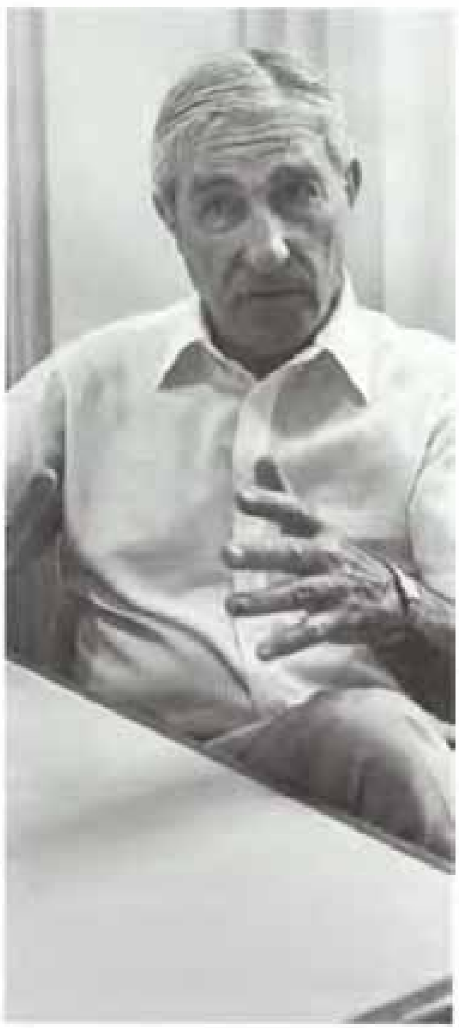
EPRI's Executive Vice President Richard Balzhiser attended both IRM symposia and gives them high marks. They brought together many movers and shakers, nominal opponents, of whom Balzhiser says with intentional irony, "We hadn't met each other, had only seen pieces of each other, and had known interaction only third-hand." Udall reached out enthusiastically and earnestly to everyone, Balzhiser recalls, always soliciting what he would call the pithy statement of fact or opinion.

Of those same occasions Udall says, "They brought it into sharp focus for me. I knew Howard Allen, of course, and I knew Charles Luce because he had been my undersecretary at Interior before he went to Consolidated Edison. I saw the industry through their eyes, saw the problems utilities have had to struggle with. I know why their adaptation, their change, is so important."

Past and future

The historian in Udall wants to understand the past, not as esoterica but as a tool for constructive change ahead. This is another aspect of his bridge building. It explains his interest in The Archeological Conservancy, a seven-year-old foundation that has built a supportive membership of 5000 and established 40 preserves in 11 states; Udall is its chairman. Writing is an even more personal expression. It documents Udall's designs and makes them available to a wider audience.

To the Inland Empire isn't Udall's first effort as a historian, although it is his most scholarly. *The Quiet Crisis* in 1963 was a series of essays that traced American environmental attitudes and practices from earliest times. A revised edition will appear in 1988, but Udall is already at work on his next book, tentatively titled *Requiem for the Atomic Age.*



"In my view, utility executives aren't fighting environmental concern any more. They're trying to work with it . . . so that they can do what they have to do in a way that is environmentally sound."

"That age parallels my adult years almost perfectly," he points out, "and it was supposed to transform our lives. But it has largely failed to do so."

Udall injects a quick disclaimer. "You can't put me in any pigeonhole on nuclear power, but I think it has gotten itself into deep trouble and is really in a holding pattern now, not primarily because of environmental objections but because of economics."

Misunderstanding and confusion were mainly to blame, in Udall's view. Expectations of others went unquestioned—for example, that the federal government, which undertook to promote nuclear power in the 1960s, would somehow pick up the tab. And there was haste. Udall agrees with Admiral Hyman Rickover's observation that the nuclear power industry was in too big a hurry.

Here again, Udall makes lemonade from the lemons. "With the passage of time, I think some of the controversy is draining out of nuclear power issues, so we can come back and look at them in a straightforward way. Maybe it isn't such a bad thing to start over, watch what happens in France and Japan, and learn from them."

The comment illustrates how it is sometimes difficult to know whether Udall's eye is on the product or the process. Most often it seems to be on the process, the people. If they are open and truly objective, then a workable solution will appear by consensus. Moreover, it will have momentum throughout its development and implementation because everyone has a stake in it.

Udall ascribes something of this talent to EPRI. He sees EPRI as a balance wheel for an industry that is far more diverse than is usually realized. "Turning to EPRI is a way for a utility in Georgia or Maine to get a focus that it couldn't have 20 years ago, a focus on where the industry is headed, what trends are emerging, what best decisions have been made recently and how to benefit from them.

"There used to be a lot of parochialism, still is in a few places. But I think EPRI makes it easier for companies to get a sense of focus for the decisions they make."

Asked what EPRI does best, Udall replies, "You put things together. You're an example of industry organizing itself to develop technology breakthroughs—very specifically, Cool Water, where you brought different entities together and got a research effort on-line."

The Cool Water project is a 100-MW power plant, now in its fourth year of operation by Southern California Edison, demonstrating the economic and environmental performance and the reliability of coal gasification integrated with combustion and steam turbines to drive electricity generators. EPRI organized the research, utility, manufacturing, process design, government, and architect-engineering organizations that have shared the project effort and its costs since the late 1970s.

Environmental progress with coal

It isn't lost on Udall that Cool Water was designed and built on the premise of using coal in an unprecedentedly clean manner. "Coal! Dug out of the earth. Ugly. Primitive, compared with what we might have expected. The power industry today is in a much different posture than it thought it would be 15 years ago."

But even with integrated gasification–combined-cycle technology for coal-fueled power generation, utilities aren't out of the environmental woods, Udall acknowledges. "Of all the pollution problems before us today, acid rain is the most excruciating, a battle between regions." The situation is not unlike the 1960s battle over water pollution control. "Rivers don't pay any attention to state lines, either," he remarks.

Asked what might be the process toward an acid rain solution, Udall echoes a conviction that he expressed in *The Quiet Crisis*: "For any one state or any one region to allow its enterprisers an economic advantage by permitting damage illegal elsewhere is a repetition of the nineteenth-century story of the forest raiders and the hydraulic miners."

In accordance with that sentiment, Udall's administration sought national standards for water pollution control. "You've got to have a regional or national solution, and everyone's got to pay part of the bill.

"All the polls I read tell me that a hefty majority believes we can have clean air and clean water and that we can get the job done. One region needn't be the dumping ground so others can enjoy a good environment.

"I think we're beginning more and more to look at global problems. We'll have to develop acid rain solutions where the entire community, or the country as a whole, contributes, doing it for the benefit of future generations."

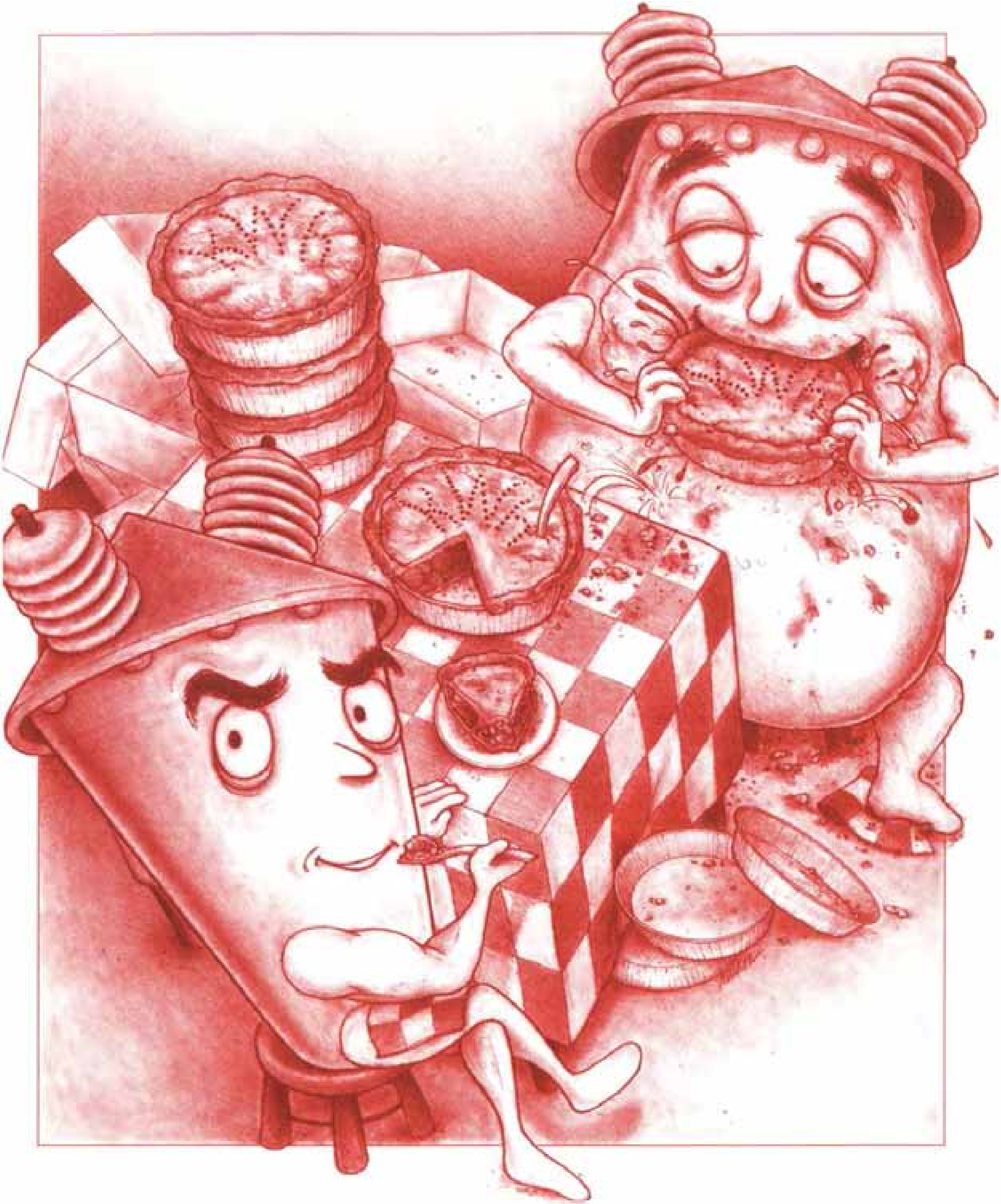
Udall is impatient to get started. He wants to get past the classic sulfur and nitrogen oxide air pollutants. He realizes that even the clean coal technology being showcased today doesn't deal with the carbon dioxide (also produced by fossil fuel use) that is leading to a global greenhouse effect and consequently a warmer atmosphere.

"When I talked to Dick Balzhiser, he said, in effect, if the Cool Water technology was more widely in use, it would be easier to attack carbon dioxide, perhaps extracting it chemically.

"That's the kind of pragmatism I like. If you simply accept the proposition that coal is dirty and produces such-and-such by-products, so we can't use coal anymore, then I see a very dark future.

"But in some ways I'm more optimistic now than I've been in the last 10 years. We're thinking more environmentally. And we're doing more real problem solving." ■

This article was written by Ralph Whitaker, *Journal* feature editor, and is based on an interview with Stewart Udall.



Transformers invariably eat up kilowatthours through losses in the core caused by magnetic friction. Cores made of amorphous metal ribbons reduce the appetite of new distribution transformers to about a third that of conventional units.

Transformers With Lower Losses

The challenge is a familiar one: A major energy-saving technology is shepherded through several years of R&D, survives extensive field trials, then finds only a limited market because of high initial cost. Traditionally, the problem of how to lower the price of a fully commercialized product rested with the manufacturer alone. However, an ongoing project being carried out by EPRI and General Electric on the manufacture of a new type of transformer illustrates how a more cooperative approach can benefit utilities and, ultimately, their customers.

The amorphous core transformer, developed under EPRI research, uses innovative materials to significantly raise efficiency. All transformers dissipate some energy, even when there's no load to serve. Use of amorphous metals in a transformer core can reduce such no-load losses by 60–70% because their atoms are randomly oriented rather than bound into a crystalline lattice. That means, if all the 20–40 million distribution transformers in service today were replaced by units with amorphous metal cores, the energy saving would be 6–14 billion (10^9) kWh per year. The value of this energy would thus represent an annual saving of $300–$700 million.

Of course not all existing units are going to be replaced overnight, but about one million distribution transformers are sold each year. Such a substantial market can offer significant incentives for introducing a new technology. At today's prices, however, amorphous core transformers could expect to penetrate only a small fraction of that market.

What EPRI and General Electric hope to do over the next several years is to lower the manufacturing costs of these energy-efficient transformers enough to make them competitive for about half of the market, assuming continued reductions in the cost of the amorphous metal itself.

During the 1950s and early 1960s, when demand for electric power was growing rapidly and distribution transformers were sometimes in short supply, a utility's decision on which transformer to buy was based largely on when it could be delivered and whether it could be serviced locally. Later, as supplies grew, price and quality became the chief considerations. With declining load growth and increasing energy costs in the 1970s, however, came the need to evaluate the total owning cost (TOC) of a transformer over its expected 30-year lifetime.

TOC consists of two components, initial price and subsequent operating costs. A major portion of the operating costs results from the no-load losses, which are much lower for a transformer with an amorphous metal core. (Additional losses, caused by resistance in the transformer windings when a load is connected, are essentially unaffected by core type.) The price of an amorphous

Finished transformers

Transformer Manufacture

Long ribbons of amorphous metal are produced by spraying a stream of liquid metal alloy onto a chilled rotating wheel, which hardens the metal before it can form a crystalline structure. Transformer manufacturers wind these metal ribbons into transformer cores many hundreds of layers thick. Tests have shown that losses from amorphous core distribution transformers are only about one-third as large as those from conventional transformers and that they have equivalent service lives.

Calculating Costs

The higher purchase price of amorphous core transformers can be offset by their lower losses, which reduce operating costs over the life of the transformer. The decision to purchase a conventional or amorphous core transformer depends primarily on what value these losses represent to a particular utility. The sample calculation shown here demonstrates that the break-even point in total owning cost for a 25-kVA distribution transformer occurs when no-load losses are valued at about $5 a watt; advances in the manufacturing process are expected to reduce the cost of the amorphous transformers to the point that they can compete at about $3 a watt.

	Core	
	Conventional	Amorphous
Cost of losses		
No-load losses	48 watts	18 watts
	× $5 watt	× $5 watt
	$ 240	$ 90
Load losses	284 watts	249 watts
	× $1 watt	× $1 watt
	$ 284	$ 249
Total losses	$ 524	$ 339
Purchase price	510	695
Total owning cost	$1034	$1034

Molten alloy spray

Amorphous metal ribbon

core transformer is now approximately 36% higher than that of a conventional transformer, so the question of which one has the lower TOC depends on how much the losses are worth to an individual utility.

Calculating the value of losses is a complicated process, involving consideration of such variables as energy cost, cost of plant, interest rates, demand charges, and the marginal cost of replacement power. Although this sort of evaluation was seldom used before 1970, about 90% of distribution transformer purchases are now based on such approaches. Generally speaking, a utility with surplus generating capacity will assign a lower value to losses, while a capacity-constrained utility may assign a higher value.

Because of the great diversity of American utilities, the value placed on no-load losses ranges from less than $1 per watt to more than $10 per watt over the expected 30-year lifetime of a transformer. The industry average runs about $3 per watt. Currently, amorphous core transformers have a competitive TOC, compared with conventional transformers, only for core loss evaluations of $5 per watt or more. That's high enough to restrict their economic advantage to about 5% of transformer sales.

For amorphous core transformers to become competitive for 50% of the market will require bringing their initial cost down enough to produce a competitive TOC for core losses priced at $3 per watt or less. Part of this decline must come from reductions in the price of amorphous raw materials. Last year amorphous metal was selling at about twice the price of the silicon steel used in standard transformer cores. As larger production facilities are brought on line, this cost differential is expected to drop significantly over the next couple of years. For the $3 per watt TOC goal to be met, however, cost reductions will also be needed in the transformer manufacturing process.

Development and commercialization

During the late 1970s, as amorphous metals became commercially available and as economic evaluation of core losses grew in importance, various manufacturers began to investigate the feasibility of building amorphous core transformers. In January 1983 EPRI initiated a program to accelerate this development through construction of a pilot manufacturing facility and extensive field testing of the transformers to be made there. Cost-sharing partners in this development program included General Electric and the Empire State Electric Energy Research Corp. (Eseerco).

The transformer cores were to be fabricated from ribbons of an amorphous metal alloy, Metglas, developed under EPRI contract by Allied (now Allied Signal). Initially, 28 preprototype transformers were constructed essentially by hand. The transformers were single-phase units, rated 25 kVA at 15 kV, with 95 kV BIL (basic insulation level). Twenty-six of these were installed on utility systems to obtain field performance data and to make sure the amorphous cores would be stable under normal operating conditions. Two others were subjected to accelerated-aging tests.

Because it is very difficult to cut amorphous alloys, which are exceptionally hard and brittle, the cores of these first transformers were made from double loops of amorphous metal, through which a single coil was wound without cutting the core. The field trials showed that core losses remained essentially unchanged, while aging tests indicated that the transformers should have a service life equivalent to conventional silicon steel transformers.

On the basis of experience gained in fabricating and installing the preprototype transformers, an alternative design was developed for use at the pilot man-

Making the Metal

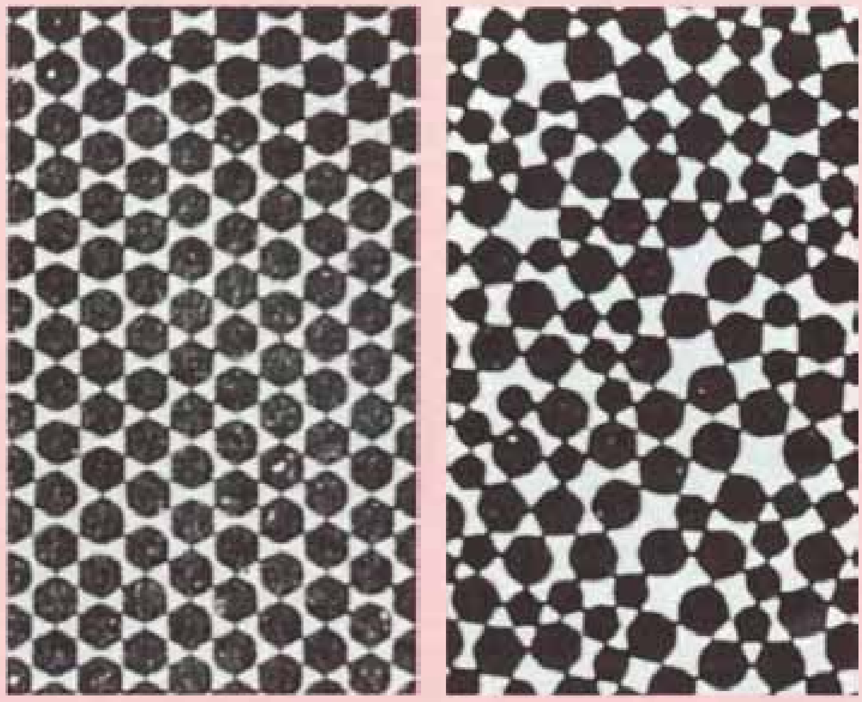
The unique properties of amorphous metals result primarily from the way they are cooled. When molten metals are cooled gradually, their atoms arrange themselves in an orderly pattern, forming tiny crystals. If cooled suddenly enough, however, the atoms do not have time to form crystals and instead freeze in a random arrangement. This amorphous internal structure is similar to that of glass, so alloys produced this way are sometimes called metallic glasses.

The noncrystalline structure of amorphous metals has a profound effect on their magnetic properties. "You can think of the interaction between a magnetic field and the atoms of a metal as a kind of molecular friction," says Senior Program Manager William Shula. "Iron atoms act like tiny permanent magnets, which get flipped back and forth 60 times a second in response to the changing magnetic field in a transformer. If these permanent magnets—or more properly, the magnetic dipoles of atoms—are lined up, it's much harder to flip them than if they are arranged randomly."

Cooling a metal fast enough to prevent crystal formation is difficult in practice but simple in principle. Conceptually, a thin stream of liquid metal is sprayed through a nozzle onto the chilled surface of a moving substrate, such as a rotating wheel. The metal solidifies almost instantaneously and comes off the substrate surface as a continuous ribbon at speeds of nearly 60 miles an hour.

The amorphous metal used in EPRI-sponsored transformer work is an alloy of iron, boron, and silicon. Called Metglas, a trademark of Allied Signal, which holds patents on its production, this metal was first produced in ribbons about one-inch wide. Loops made from this ribbon were stacked five deep to create the cores for the preprototype transformers. Currently, six-inch-wide ribbons are being used to make the cores in General Electric's commercial transformers.

Unlike most metals (left), which take on a regularly patterned crystalline structure as they cool, amorphous metals (right) retain a more-random internal structure that gives them unusual physical and magnetic properties.



Eventually, amorphous metals may become less expensive than the conventional silicon steel used to make core laminations. One-step, continuous ribbon production is an important factor in meeting this goal because conventional materials require six to ten manufacturing steps. In addition, amorphous metal requires only about 20% of the energy needed to produce silicon steel. When amorphous metals first became available in the late 1970s, they cost nearly 100 times as much as silicon steel. Today, the cost ratio is less than 2:1, and the two metals may reach parity by about 1990. Volume production, of course, will be the key to declining cost, so the recent announcement by Allied Signal that it will build a 60,000-ton-per-year production facility has raised considerable interest among transformer manufacturers. □

ufacturing facility in Hickory, North Carolina. The new design incorporated a single-loop core with two coils. Installing the coils involved cutting the core and then reassembling it so that the numerous layers of amorphous metal ribbon fit together precisely. This tricky procedure—details of which remain proprietary—proved to be one of the key engineering achievements in development of a transformer that could be manufactured in sufficient quantity for commercial feasibility.

The Hickory plant produced 1000 overhead distribution transformers with 25-kVA rating and shipped them to 90 EPRI member utilities during 1985 to begin a two-year field trial. Utilities participating in this field demonstration agreed to measure core losses and exciting currents when they received the transformers and then to test 10% of the units on their systems each year during the following years.

All testing to date has confirmed that the core losses have remained stable. There has been no failure of either the preprototype or prototype units that could be attributed to the amorphous metal core. Only five of the 1000 demonstration units have been returned for repairs, following such typical real-world incidents as being struck by lightning, falling from a utility pole, and being subjected to three times rated load.

The success of this demonstration program led General Electric to announce commercial availability of 25-kVA and 50-kVA single-phase distribution transformers, both pole-type and padmount, in 1986. The company is now offering single-phase transformers from 25 kVA to 100 kVA and three-phase transformers from 75 kVA to 500 kVA in any standard combination of primary and secondary voltage. In addition to General Electric, which has now sold thousands of units of various sizes, other manufacturers making amorphous core transformers include Westinghouse Electric, McGraw-Edison, and Kuhlman. EPRI also has a separate program under way devoted to improving substation power transformers, the cores of which are fabricated from consolidated amorphous metal strips that are cut and stacked, as opposed to the wound-core designs used in distribution transformers.

In recognition of the importance of their joint effort, EPRI, General Electric, Eseerco, and Allied Signal have received the 1987 International Engineering Materials Achievement Award of the American Society for Metals. The society cited development of the amorphous core transformer as "a major advance in the efficiency of electric power distribution systems."

Bringing down costs

Now that the first transformers have been commercialized, the task remains to make them competitive in a large segment of the market. From a manufacturing standpoint, this will require introducing a higher degree of automation to the fabrication process. Part of the problem is the larger amount of material handling involved in making the new transformers. The ribbons of amorphous metal used in a core are one-thousandth of an inch thick—about one-tenth the thickness of conventional core silicon steel. Thus more laminations are needed, and the task of realigning cut pieces becomes more difficult.

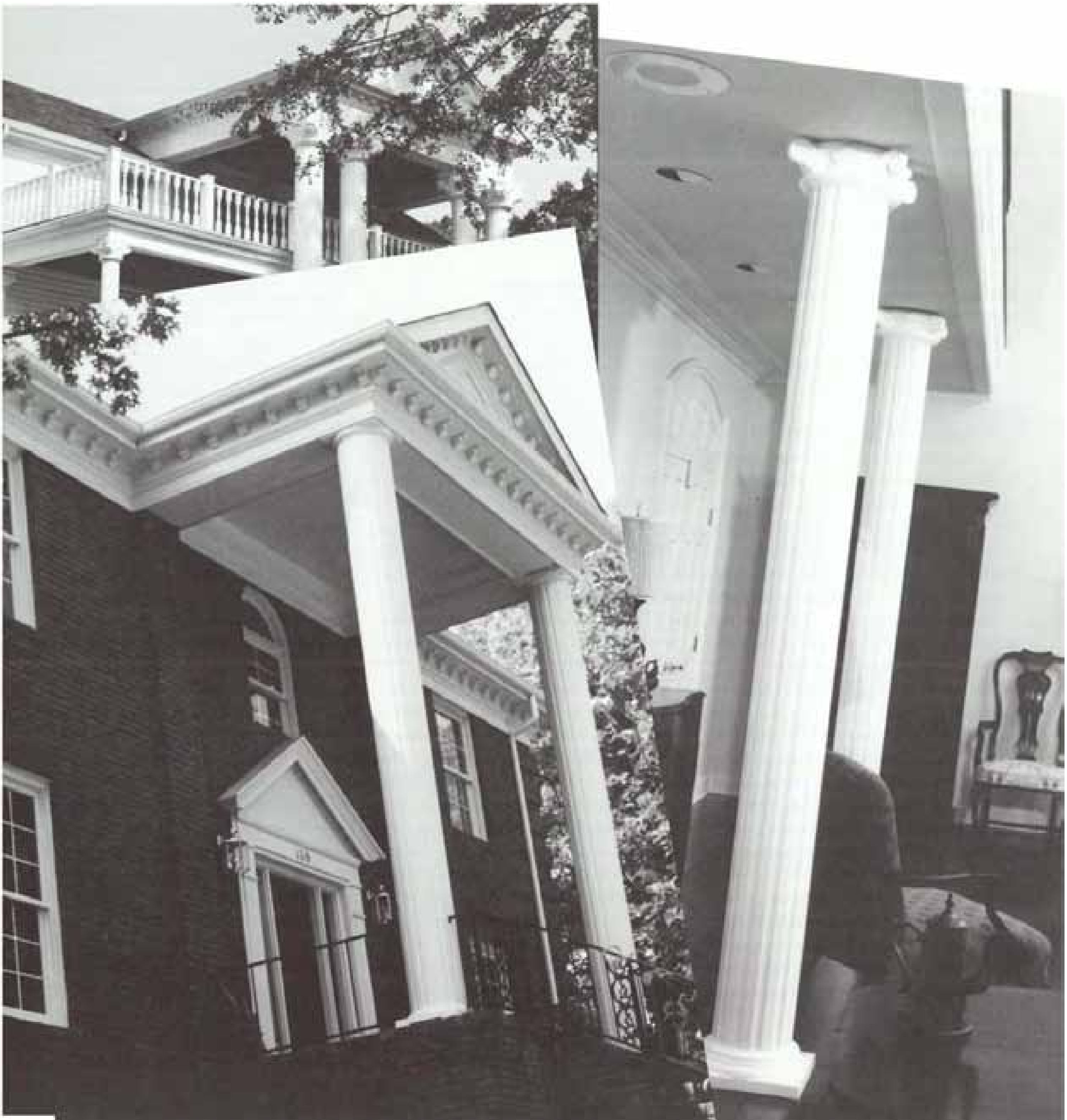
In addition, the ribbons have a surface finish that is less uniform than that of silicon steel, which means more space is wasted in each turn of a core loop. This variable is measured as core space factor—the ratio of the cross-section area of the core actually filled by metal to the area potentially available. A conventional steel core has an excellent space factor, 96%, compared with only about 80% for an amorphous metal core. Because of this, an amorphous metal core transformer needs a larger core volume than one made of conventional steel to get the same kVA rating. Such an increase, of course, contributes to the higher cost of the transformer.

Another factor that affects core size is the ability of a metal to respond to magnetic fields without saturating. Electrical energy is transferred from the primary to the secondary coils of a transformer by the magnetic field set up in its core. This energy transfer increases with the intensity of the magnetic field only up to the saturation point of the metal; beyond this point, more metal must be added to the core. Amorphous alloys have lower saturation points than conventional steel, which also contributes to the larger size of their cores. (To achieve comparable no-load losses, however, a silicon steel core would have to contain even more material, making it uneconomical.)

Working within the framework of these mechanical and electrical limitations, EPRI's current project with General Electric aims at reducing the cost of making transformers with amorphous metal cores. At the same time, steelmakers are also investigating a variety of methods for reducing the losses of silicon steel transformers. Such competition sets the stage for significant changes in the transformer market, which will most likely provide opportunities for both conventional and amorphous core units for the foreseeable future. "This competition will provide utilities with transformers that are both more energy-efficient and more cost-effective, whatever their configuration," says Project Manager Harry Ng. "EPRI's role from the start has been to foster technical innovation in this area, first by stimulating development of amorphous core transformers and now by working to lower their cost. This effort represents a part of EPRI's ongoing commitment to technology transfer, even when it involves improving manufacturing techniques." ■

This article was written by John Douglas, science writer. Technical background information was provided by Bill Shula and Harry Ng, Electrical Systems Division.

Electrotechnologies can pay off in higher productivity and lower fuel costs for manufacturers—and you don't have to be an industrial giant to benefit. Infrared curing technology made the crucial difference for a family-owned company that makes coated aluminum columns.



An Electrotechnology Case Study

Supporting Business With Infrared Processing

"I'd rather spend my time creating a new manufacturing process than playing golf," says William Smith, Sr., chairman and founder of Moultrie Manufacturing. Of all the creations and achievements that have distinguished Mr. Smith and his family metals processing and fabrication business over the past 35 years, none is quite so remarkable as the electrically powered, infrared (IR) curing oven that Mr. Smith and his son, William Jr., and daughter, Anne, installed at their Moultrie, Georgia, manufacturing plant in 1984–1985.

The Smith family, with their willingness to invest in new technology and their hands-on approach to managing a business, are representative of American industrialists who are using electricity-based manufacturing to prosper in changing times. Their IR curing system, which replaced a much larger and less-efficient gas-fired curing oven, is just one of several electrotechnologies that are helping American industries improve productivity, meet environmental standards, and compete in a global economy.

The proven success of electrotechnologies like IR curing has an encouraging significance for electric utilities. Increasingly, utilities are becoming aware of the productivity benefits of electrotechnologies and the important, sometimes saving, role that electrification can play for industrial customers. Recognizing their own stake in a healthy industrial economy, many utilities are offering customers the technical assistance and bottom-line information they need to put electrotechnologies to work.

As part of these efforts, the story of the Smiths and their IR curing system was recently documented by the Center for Materials Fabrication (CMF), an EPRI-sponsored R&D applications center at the Columbus Division of Battelle Memorial Institute. Through a program of subscription publications, technical assistance, and coordination and funding of technology demonstrations at industrial sites, CMF brings utilities, manufacturers, and vendors together to develop and apply electrotechnologies. These include IR curing of the kind in use at Moultrie, along with other technologies for fabricating materials, such as induction heating, laser processing, computer-aided manufacturing, and radio-frequency heating and drying.

As documented by CMF, IR curing at Moultrie provides just one example of an electrotechnology and its role in maintaining a manufacturer in robust, good health. "A case study like Moultrie can be used by utilities as a reference or as a marketing tool," says Robert Jeffress, EPRI project manager for materials production and fabrication. "At the same time, we hope to encourage utilities to get involved in marketing and technology transfer activities that could help solve crucial problems for many industrial customers."

The time was now

For William Smith, Sr., and Moultrie, electric IR curing presented itself as a solution to two problems that had come to bear on the family business in the 1980s: the need to comply with the regulations of the federal Environmental Protection Agency (EPA) and the need to head off foreign competitors who were threatening to undersell the company's aluminum architectural products.

Although Moultrie also makes aluminum furniture, about 50% of sales come from coated aluminum columns of the type that stand in front of southern mansions and other neoclassical buildings. Traditionally, these columns were cut from wood or stone; but in the 1960s Smith Sr. devised a method to join pieces of coated aluminum into a low-cost, strong, and durable column that quickly became a commercial success. Smith Sr.'s wife, Anne, helped speed the company's success by drawing designs for what became an expanding line of columns and accessories in different styles and sizes.

In 1983, however, the Smiths received warnings from state inspectors that waste compounds released into the atmosphere at their plant were in excess of EPA limits. At the time, the company used liquid paint to coat the column pieces and a gas-convection oven to dry them. In the drying process, paint solvent containing the regulated compounds was discharged into the atmosphere.

During this same time period, as Smith Sr. investigated solutions to the EPA problem, he became aware of a Japanese group considering an entry into the aluminum column market. "We were at a housing industry trade show in Houston in 1983, when our booth was visited by a group of Japanese businessmen with calculators in hand," as Smith Sr. tells it. "Soon thereafter, we received an inquiry

The Benefits of IR Curing

The Moultrie Manufacturing Co. combines a solids powder coating system and an IR oven in an all-electric finishing line that provides several advantages over curing in a gas-fired oven.

Increased production. The same eight-hour shift now produces 10,000 pieces, rather than 300. It now takes only 34 seconds at 55 ft/min to cure the powder coating, compared with 90 minutes for curing in a gas-fired oven.

Material saving. More than 99% of the powder coating is applied to the columns, with Moultrie saving 25% over the cost of liquid paint.

No pollution. Because the powder is all coating material, there are no toxic fumes or solid wastes to remove and no problems with EPA regulations.

Flexibility. The powder application system makes it quick and easy to switch coating color.

Space saving. The IR oven is only 7 feet wide and 30 feet long, about one-fortieth the size of a comparably powerful gas-fired oven.

Energy saving. The system allowed Moultrie to reduce monthly energy costs by nearly 50%.

Process control. IR emitters turn on and off very quickly, allowing operators to reduce power as soon as product leaves the oven. In addition, sensors and computerized controls will detect changes in line speed and reduce power to prevent burning.

Improved work environment. The IR oven doesn't heat up the surrounding area.

Application of powder coating

Infrared oven

Process control computer

from a Japanese company, asking if we would be interested in serving as distributor for their own columns. I said to my son, Bill Jr., 'If we don't improve productivity and hold our prices down, we're going to find ourselves in a battle. Now is the time to modernize.' "

As a former General Electric project engineer who helped design and build manufacturing systems at its Nela Park light bulb plant in the 1940s and 1950s, Smith Sr. was determined to assemble a new finishing line that would represent the state of the art. He didn't hesitate to investigate technologies with which he was unfamiliar.

After exploring the available options, Smith Sr. decided to anchor the new finishing system with a shortwave IR oven. Some 600 high-intensity emitter lamps line the inside of the oven, which is 30 feet long and 7 feet wide. The lamps are quartz tubes containing tungsten filaments, which emit short wavelength IR radiation when electrically heated to a maximum temperature of approximately 4000°F. More intense than the medium- or long-wave IR radiation used in applications that require less heat, shortwave IR heats quickly and penetrates deeply into the material being processed.

To harness the power of shortwave IR, the Smiths combined the new oven with a 100% solids powder coating system that eliminates the environmental problems caused by the old system of gas-drying and liquid paint. In an all-electric system, the powder coating is applied electrostatically to the aluminum pieces as they move toward the oven on a conveyor system originally designed for the laundry industry. Smith Sr. and his son and company president, William Jr., recognized the potential in this laundry-industry system and converted it themselves to carry more weight.

As the pieces travel through the oven at a speed of 55 feet a minute, the IR radiation melts the powdered coating into a lustrous finish and bonds it to the aluminum. To keep pieces from being burned or finished unevenly, the entire coating, curing, and conveyor system is programmed and tightly controlled by a front-end computer. The operator punches instructions to the system through a keyboard and uses a CRT to monitor parameters transmitted from sensors in the oven.

Integration and installation of the new system, which has been hailed by experts as one of the most advanced and efficient finishing lines in the United States, became a year-long labor of love. The Smiths prepared for the new system by putting up a new building of some 30,000 square feet to house the system and related pretreatment and packaging facilities. This would have been impossible if the Smiths had opted for a comparably powerful gas-fired oven, which would need to be 40 feet wide and at least 200 feet long. "To get similar results from a gas oven, we'd have to give it its own building," says Smith Jr. "With the electric IR oven, we can package the coated pieces in the same building and improve productivity even further."

Smith Sr. and his family had a hands-on role in nearly every aspect of the construction and installation project. From the start, Smith Sr. and Smith Jr. poured concrete and drove heavy equipment. After the building was completed, father and son pried open the crates containing the various system components and installed them on the factory floor. Smith

CMF: Utilities Getting Involved

Inventive rate structures are just one of several ways that utilities can act as catalysts in electrotechnology applications. At the Center for Materials Fabrication the staff is helping utilities expand their participation in electrotechnology marketing and installations. "Not every utility customer is going to be as mechanically adept and as gung ho as the Smiths," says John Bush, CMF project manager for IR technology. "That's when the utility can step in and help acquaint the customer with the functions and the benefits of electrotechnologies."

To help utilities fill this role, CMF produces technology transfer reports, case studies, and newsletters. In addition, the center maintains a subscription service to provide utilities with detailed technology updates and management overviews; the Metaline, offering free consultation over the telephone; and audiovisual technical tutorials. CMF, with the support of utilities, is also collaborating with industrial companies to develop electrotechnology demonstration projects for innovative applications.

Having documented more than a dozen electrotechnology success stories like the one at Moultrie, CMF is becoming an active participant in success stories now in the making. As demonstrated by the Smith family and their new curing and coating system, industrial electrification and revitalization become realities when technical ingenuity is combined with a concerted effort. Those who might not share in such optimism can turn for inspiration to the image of William Smith, Sr., installing all 600 emitter lamps in his electric-powered oven.

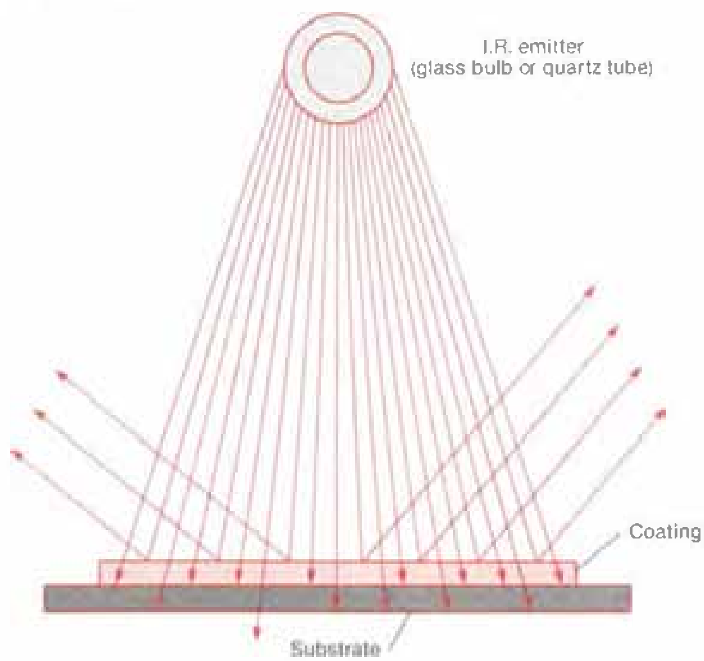
A New Wave of Infrared Technology

Infrared (IR) process heating has been in use in United States industries since the 1930s when Ford Motor adopted and developed it for curing finishes on automotive bodies. For nearly half a century, use of the technology was limited by difficulties in controlling IR emitters and adapting them to specific applications. More recently, however, improvements in emitter tubes, in electronic process control, and in solids powder coating systems have combined to create a new IR technology that is coming into expanded use for curing and drying applications in the metals processing, automotive, textiles, home appliance, paper converting, plastics, and other important industries.

IR radiation occupies the part of the electromagnetic spectrum between visible light and radio waves. IR wavelengths range from 0.8 to 1000 micrometers, with the band between 0.8 and 3.3 micrometers most effective for industrial curing and drying.

Medium-wave IR (2.3–3.3 micrometers) emitters consist of open-ended glass or quartz tubes containing wire coils that can be heated to temperatures of 1800°F. These wavelengths are used in applications where a lower temperature, more diffuse source of heat is required, such as in drying water from metal or plastic surfaces or curing inks on paper or screen-printed fabrics.

IR emitters provide process heat that can be focused, concentrated, directed, and reflected in a manner similar to light. Rather than heating air inside an oven and relying on convection to heat and cure coatings as gas-fired ovens do, IR emitters focus radiation directly on the material and coating being processed.



Shortwave, or high-intensity, IR systems, such as those at Moultrie Manufacturing, use tungsten filaments heated as high as 3000–4000°F to emit radiation in the wavelengths between 0.8 and 2.2 micrometers. This radiation is used where intense, directed heat is required, such as in curing thick coatings, or in high-speed conveyor lines for curing coatings on metal or wood products.

IR is just one of the forms of electromagnetic radiation that has come into wide use over the past 15 years to modify materials in many different industries. New electrotechnologies use the full spectrum of electromagnetic radiation energies, including ionizing radiation (e.g., X rays, high-energy electrons, plasmas) and nonionizing radiation (e.g., ultraviolet, microwave, radio frequency, and IR). □

Jr., a skilled mechanic and technician, worked at tasks that ranged from the adjustment of compressor set points to the positioning of sensors in the IR oven. Smith Sr.'s daughter, Anne, a former systems analyst at IBM and Moultrie's vice president for marketing, worked closely with the oven vendor and consultants to program the system's process control computer. And in this age when executive talent is more often focused on arbitrage than on the factory floor, Smith Sr. took the job of leaning into the oven and installing all 600 IR emitter lamps.

When the components had finally been put together and the oven tuned to its characteristic orange glow, the Smiths had spent roughly $450,000 on the oven and coating system and $1,000,000 on the entire construction project and equipment installation.

An IR cure for what ails you

Although a million dollars is a sizable investment for a company like Moultrie, which earned about $6 million in sales in fiscal 1986, the company has improved productivity and reduced operating costs so markedly that the Smiths expect the system to pay for itself in three years. Moultrie, an unusual company in more ways than one, paid for the project without borrowing any money. The benefits of the new system, however, could also make the financing of similar installations an attractive option for both borrower and lender.

Since installing the system in 1984, Moultrie has increased sales at a rate of about 12% a year, while holding prices at 1980 levels and improving the durability and luster of the finish on their columns. In addition, Moultrie eliminated problems with EPA and warded off foreign competitors, who have apparently backed away from the aluminum column market.

The productivity gains resulting from reduced curing time are exponential, with the new system curing the same quantity of pieces in 34 seconds that took an hour and a half to dry in the gas-fired oven. Moultrie now produces 10,000 coated column pieces during a half-day shift, compared with 300 finished pieces during a full-day shift with the old system. This frees the operators to dedicate the second half of their shift to packaging the columns.

The system's computerized process control adds to these gains by virtually eliminating burned or poorly coated pieces. The operators also have the flexibility to adjust the coating and curing system to finish column pieces like caps and bases that once had to be painted by hand. Servo motors and power controllers in the oven walls allow operators to control the power and position of the emitter lamps to meet different heating requirements. In contrast to batch-style drying in the gas oven, the new system allows Moultrie to cure different pieces according to specific recipes that are programmed on the process control computer and then activated by simple keyboard commands.

On top of these advantages, the new system helped the company reduce costs for materials and for cleaning and maintenance. The old system of spray painting was messy and wasteful; only 40% of the paint actually adhered to the columns, and the line had to be shut down for cleaning a half day each week. The new system, by contrast, recycles the powder so that at least 95% of the coating is used, and very little maintenance is required. By switching to powder, Moultrie reduced paint costs by 25%.

Overall, the electrically powered system provides a cleaner and more comfortable environment in which paint splatter and toxic fumes have been eliminated—and where there is no difficulty meeting EPA standards. The factory environment around the IR oven is also cooler than during the gas-oven days. Because the IR is focused so intensely on the column pieces and because the system is extremely efficient for energy, very little heat is released into the surrounding area.

The energy efficiency of the new system is another source of cost saving for Moultrie. Compared with gas ovens, which take several minutes or hours to either cool down or come to full temperature, the IR emitters can be turned on and off almost instantly. "We no longer have to heat the whole world every time we use the oven," says Smith Sr. "We can reduce power as soon as pieces leave the oven, and that helps us save energy."

The efficiency of the new system allowed the Smiths to reduce their monthly energy costs from $2400 to $1100, partly by taking advantage of the load management program and off-peak demand charges offered by Colquitt Electric Membership, the local distributor of electric power. "Our utility had already helped us with off-peak charges for the electric furnace we use to melt aluminum ingots," Smith Sr. explains. "Before we went ahead with the new installation, we met with the utility member services people and established that by keeping the system idle during certain peak hours, we could cut our electric bills and pay less for electricity than we did for gas." Running the new system on a four-hour shift (which wasn't possible with the old system) also helped Moultrie restrict operations to off-peak hours and pay less for energy. ■

Further reading

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This article was written by Jon Cohen, science writer. Technical background information was provided by Robert Jeffress, Energy Management and Utilization Division.

TECH TRANSFER NEWS

SCE Uses Tools for Marketing Cool Storage

EPRI's Energy Management and Utilization Division has developed an array of tools to help utility customer service personnel promote and market technologies for demand-side management (DSM). Southern California Edison (SCE) is now using two of these tools, the "Cool Storage Presentation Materials" and the *Commercial Cool Storage Design Guide*, to achieve a primary DSM objective: influencing customers to install off-peak cooling systems, also known as cool storage technology.

Since 1986 SCE's cool storage DSM program has included direct marketing to customers, full payment or cost sharing for system feasibility studies, equipment installation incentives, and reduced off-peak electric rates. This program, which relies heavily on direct contact with customers, has earned an enthusiastic customer response. SCE projects that 154 MW of load will be shifted off-peak to cool storage systems by 1993.

EPRI-developed tools are helping SCE achieve its goal. The utility uses "Cool Storage Presentation Materials," a slide show with accompanying handbook, in regularly scheduled in-house seminars to educate energy services representatives about the principles of cool storage, system design issues, and possible applications of the technology. The representatives then distribute the *Commercial Cool Storage Design Guide* to interested engineers and architects to provide guidance in system design. SCE has distributed over 800 copies of the document since June 1986.

SCE's expanding involvement in off-peak cooling began in 1978 with the successful demonstration of an ice-on-coil cool storage system at an electronics manufacturing company. In 1982 an SCE proposal to the California Public Utilities Commission concerned a formal cool storage DSM program that would offer customers financial incentives for system installation. The proposal was approved, and 28 SCE customers had installed cool storage systems by 1985, producing a 10-MW load shift from peak to nonpeak hours. On the basis of this success, SCE then decided to focus its DSM efforts on off-peak cooling and to bolster financial incentives and accelerate promotional efforts.

The current program, adopted in 1986, offers special time-of-use rates for customers who shift cooling load to off-peak hours, and minimum rates for customers' shifting that load to the hours between midnight and 6 A.M. The financial incentives include payment of up to $10,000 for a cool storage feasibility study and payment of $200/kW shifted to nonpeak hours, up to a maximum of $300,000 per system. An incentive payment of $100/kW shifted to nonpeak hours is offered for applications involving product storage. The results of the program to date are impressive: by the end of 1987, some 111 cool storage systems are expected to be installed, with the capability to shift a total 46.5 MW of load to nonpeak hours.

"Off-peak cooling technology has given us an effective way to manage on-peak load growth and to improve minimum load conditions between the hours of midnight and 6 A.M.," says Dave Ferguson, supervisor of SCE's energy management programs. The immediate benefits of improved system load factor and operating efficiency also generate long-term benefits by helping to forestall the need to construct new generating units.

Characterization of the systems installed or soon to be installed in SCE's service area show the versatility of the technology: the systems vary greatly in size—from 7 to 1600 kW—as well as in application. For example, eutectic salt systems are used at Orange Coast College (194 kW) and at the Leisure World senior citizen housing community (504 kW) to provide air conditioning. At Yoplait USA, a 610-kW ice system is used in the production of yogurt products. In addition, a plastics manufacturing plant is installing a 429-kW ice system to cool injection-molding equipment. Other applications in SCE's service area include systems installed at schools, hospitals, office buildings, and supermarkets.

SCE's promotion of off-peak cooling stands to benefit everyone involved: the utility retains customers and improves load factor; technology users pay lower rates for electricity; the cool storage industry gains exposure and credibility;

and all ratepayers benefit from lower electricity rates. ■ *EPRI Contact: Ronald Wendland (415) 855-8958*

Preventing Rupture of Seam-Welded Pipes

The potential rupture of seam-welded steam lines is one of the most important safety concerns in today's fossil fuel power plants. A new guideline is designed to help utilities identify pipe inspection technology, assess remaining life, and make run-repair-replace decisions (CS-4774).

The guideline includes inspection results from more than 60 units, descriptions of the types of defects found, evaluations of the merits of different inspection techniques, and a road map giving step-by-step procedures for conducting an inspection program and for making run-repair-replace decisions. The guideline also provides information on the EPRI-developed SLIC steam line computer code to estimate the remaining life of high-temperature steam lines with defects of known sizes or to determine inspection intervals.

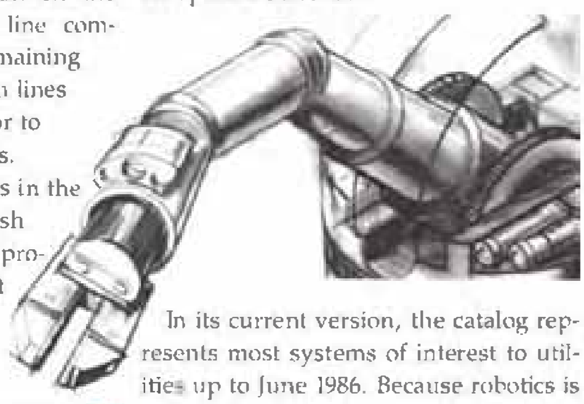
By following the procedures in the guideline, a utility can establish an inspection and evaluation program solidly based on current knowledge. A videotape about the guideline featuring field interviews with utility engineers is also available (CC86-02). ■ *EPRI Contact: Barry Dooley (415) 855-2458*

A Compendium on Mobile Robots

Mobile robots and teleoperated vehicles are used to inspect, locate, identify, manipulate, and maintain components in nuclear power plants and many other hazardous environments. For technical data necessary to match these systems to specific missions and needs, utilities and other organizations can now turn to a new catalog, *A Compendium on Mobile Robots Used in Hazardous Environments* (NP-5060).

On the basis of a literature search and interviews with users and manufacturers, the compendium includes specification sheets and photographs for more than 90 mobile robots designed to operate on floors, on outdoor terrain, and in shallow water. The listed robots are used in nuclear power plants and in many other applications, from crowd control and antiterrorist intervention to mining, construction, and fighting fires.

The catalog lists the robot manufacturers and persons to contact for information. In addition, a looseleaf version of the catalog (NP-5060P) is available with a videotape that discusses methods for matching systems to utility needs. It also proves the importance of conducting a thorough mission-task analysis to ensure an optimal selection.



In its current version, the catalog represents most systems of interest to utilities up to June 1986. Because robotics is a dynamic field, however, the catalog will be updated. EPRI intends to improve existing data and to include devices not now appearing in the catalog. Readers are encouraged to send completed specification sheets and photographs to the project manager. Two new sections will also be added as part of the update. One will cover underwater systems (mini-ROVs), and a second will present data on devices for pipe inspection, cleaning, and repair. ■ *EPRI Contact: Floyd Gelhaus (415) 855-2024*

EPRI-Developed Equipment Used in BWR Refueling

Northeast Utilities (NU) recently purchased two pieces of commercially available equipment developed by EPRI for use during BWR refueling activities.

Staff at NU's Millstone Unit 1 purchased equipment for handling control rod drives from the EPRI licensee, Nuclear Energy Services (NES) and used it for the first time in June during the summer refueling outage. Although the original prototype was sold by EPRI to Commonwealth Edison's Quad Cities Unit 2 following an in situ demonstration during its fall 1986 refueling outage, the Millstone purchase marked the first commercial sale of the equipment.

The equipment, which features a pneumatic winch and a transport elevator carriage, is designed to reduce radiation exposures and labor requirements, as well as to improve safety during the changeout of the drives on BWR control rods. At Millstone 1 this June, the maintenance staff used the equipment to successfully change out 22 of the drives, with a significant reduction in total radiation dose to workers. In addition, the maintenance staff praised the performance of the equipment and the quality of the support received from NES.

Millstone 1 also purchased a new grapple for fuel support piece (FSP) handling from the EPRI licensee, DEI Enterprises, Inc. DEI has now sold three of the grapples, which are used to remove and replace the FSP casting from the lower core support plate of BWRs and thus allow for control rod shuffle or changeout activities. Compared with similar commercial equipment, the grapple provides protection against dropping the FSPs, improved visibility during FSP handling, reduced weight, and easier maintainability. ■ *Contacts: Nuclear Energy Services (Danbury, Connecticut) and DEI Enterprises, Inc. (McLean, Virginia), EPRI licensees; Richard Burke, EPRI (415) 855-2766*

Ecological Effects

Response of Vegetation to Interacting Stresses

by Robert Goldstein, Environment Division

In the United States before 1980, there was little concern regarding the effects of acid deposition on forest vegetation. The reasons were several. No direct effects had been observed in the field. A large, long-term experimental study, supported by a Norwegian project on the effects of acid precipitation on forests and fish, reported no adverse effects on trees treated with simulated acid precipitation. Conventional wisdom held that as most forest soils were naturally acidic, forest trees had adapted to acidic conditions. Conventional wisdom also held that because the growth of most forests is limited by the availability of nitrogen, acid deposition is likely to have a fertilization effect.

In the early 1980s a hypothesis developed by Bernhard Ulrich of the University of Göttingen (West Germany) began to receive widespread attention in the United States. Ulrich hypothesized that acid deposition could produce elevated concentrations of aluminum in soil water and that these elevated concentrations could kill the fine roots of trees, leading to the reduction of tree growth and ultimately death.

Since the original elaboration of Ulrich's hypothesis, considerably more has become known about forest decline. At sites where decline occurs, trees have been shown to be subjected to multiple stresses. In addition, it is not possible to correlate the presence and severity of decline to a single stress (such as soil water aluminum concentrations) or environmental factor. These observations lead to the hypothesis that decline results from the interaction of multiple stresses and that the relative contribution of any given stress can be highly variable from site to site.

Stresses that may contribute to forest decline are atmospheric pollution (e.g., acid precipitation, acidic particulates, sulfur dioxide, nitrogen oxides, ozone, metals, anthropogenic organics); management practices (e.g., repeated harvesting, which can lead to the depletion of essential nutrients, suppression of natural fires, planting of exotic tree species); climate (e.g., drought, wind); insects; disease; natural aging; and natural succession (the process of forest development whereby as a forest ages, certain tree species characteristic of a young forest are replaced by other tree species).

Response to stress

The responses of trees to stresses are mediated by factors related to climate (e.g., insolation, temperature, precipitation), soil (e.g., moisture and nutrient availability, pH), and the trees themselves (e.g., species, provenance, preconditioning, moisture, and nutrient status). Many of these factors vary with time, as do the stresses themselves.

Past air pollution effects research emphasized dose-response studies. In a dose-response study, plant growth or yield response is correlated to air pollutant exposure without examination of the mechanism by which the pollutant produces the observed response. For purposes of research concerned only with a few plant species that grow under nonvarying environmental conditions and pollutant exposures, the dose-response approach appears to be a quick and efficient means of assessing

ABSTRACT *The response of forest vegetation to air pollution is complex: a multiplicity of air pollutants interact with other stresses to induce a response, and at the same time a large number of soil, atmospheric, climatic, and plant factors interact to mediate the response. There are so many commonly occurring combinations of important plant species, pollutants, other stresses, and environmental factors that it is impossible to determine all responses empirically. To develop a comprehensive methodology for analyzing and predicting responses, EPRI researched the response of plants to interacting stresses. The study combines mathematical modeling with laboratory and field experiments under controlled exposures and will continue for several years before obtaining results.*

potential damage. If the species of concern are many, however, and the environmental conditions under which they grow are highly variable, a process-mechanistic approach that explains how effects occur will be more efficient and effective. The results of process-mechanistic studies, unlike those of dose-response studies, can be extrapolated to species and environmental conditions other than those for which the experiments were performed. Infinite resources would be required to perform dose-response studies for all likely combinations of commonly occurring species and environmental conditions.

ROPIS

The study is supported by cofunding and cost sharing from several sources. The Empire State Electric Energy Research Corp. and Niagara Mohawk Power are cofunding research in the East. Tennessee Valley Authority is doing so in the South. Southern California Edison, U.S. Forest Service, and the National Council of the Paper Industry for Air and Stream Improvement are involved in the West.

The general objective of ROPIS is to develop a general mechanistic theory of plant response to interacting air pollutants and other stresses that will permit quantification of the relative roles of individual stresses and prediction of integrated responses (RP2799). The study addresses the complexity of the subject through a robust experimental design that exposes a variety of plant species (native to different geographic areas) to a diversity of stresses under different environmental conditions. Responses are measured across a hierarchy of biologic levels of organization, proceeding from the biochemical and physiological, through the whole plant, and eventually up to the stand and ecosystem. A variety of apparatus, including open-top field chambers and controlled laboratory growth chambers, are used for experimental treatments. The study strongly emphasizes the development and application of mathematical simulation models.

The current structure of the study is strongly influenced by international concern over forest decline and its relation to air pollution; it is anticipated, however, that the results will be applicable to agricultural plants as well as forest trees. At present, the study is divided into four major modules, which are summarized in Table 1. The first three are situated in different regions of the United States (the East, the South, and the West) and use tree species significant in these regions. There are claims that both red spruce and sugar maple are under-

Table 1
COMPONENTS OF THE ROPIS STUDY

Module	Principal Support	Plant Species	Stress	Exposure Apparatus	Modeling
East	Boyce-Thompson Institute, Cornell University	Red spruce Sugar maple	Acid precipitation; ozone	Open-top chambers	Develop model
South	Tennessee Valley Authority; Oak Ridge National Laboratory	Loblolly pine	Acid precipitation; ozone; magnesium	Open-top chambers	Use East model
West	University of California at Riverside and at Berkeley; U.S. Forest Service	Ponderosa pine	Acid precipitation, ozone, moisture	Open-top chambers	Develop model by cofunding
Basic Processes	Stanford University; Oregon State University; Pennsylvania State University; Texas A&M University	Poplar Radish	Sulfur dioxide; ozone; moisture; nutrients	Open-top chambers, laboratory chambers	Develop model

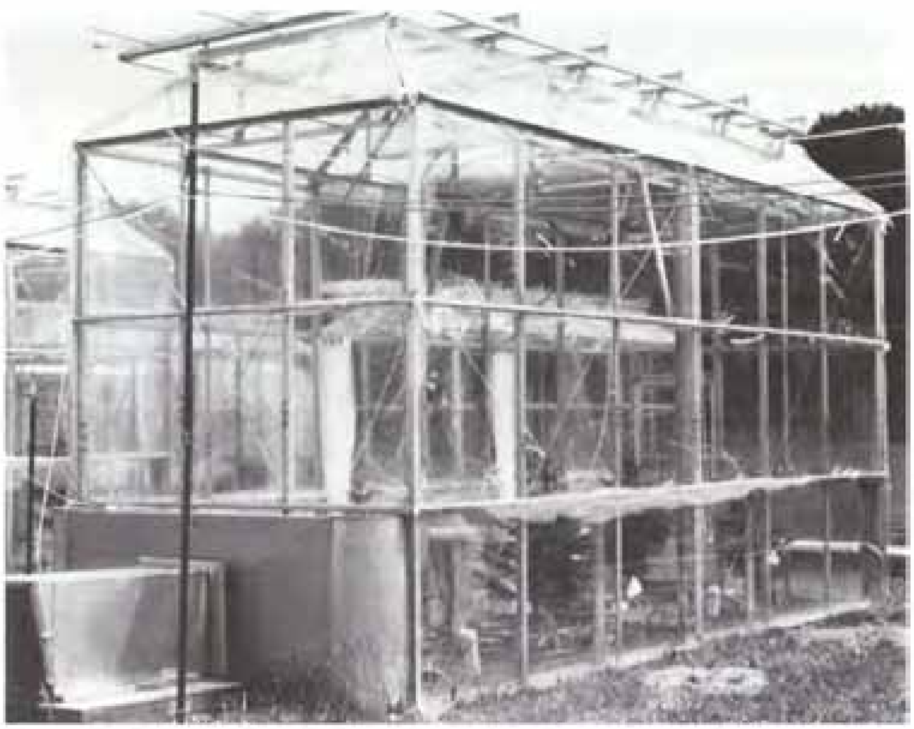


Figure 1 **Red spruce saplings growing in a ROPIS open-top chamber in Ithaca, New York. Within the chamber, saplings will be exposed to controlled acid rain and ozone treatment.**

going widespread decline in the East. Loblolly pine is the most important commercial tree species in the South, and ponderosa pine is a commonly occurring species throughout the West.

In all three regional modules, seedlings or saplings are exposed to various combinations of stresses in open-top chambers for periods of three to four years. Figure 1 illustrates an open-top chamber used for saplings in the eastern component. It is 24 ft long, 9 ft wide, and 12 ft high (~7.3 × 2.7 × 3.7 m). The chamber consists of a metal frame covered by plastic but open at the top. The objective of the chamber design is to control atmospheric gaseous pollutant concentrations within the chamber while permitting other environmental factors, such as air temperature and solar radiation, to be the same inside the chamber as they are outside. The controlled atmosphere is pumped into the side of the chamber. Maintenance of positive pressure relative to the atmosphere outside the chamber prevents leakage into the chamber through the open top. The open top prevents the buildup of moisture and heat within the chamber. Controlled acid rain treatments are applied by means of an overhead sprinkler system. Each chamber is fitted with a movable overhead shield, activated by a rain sensor. When natural precipitation occurs, the shield covers the chamber.

Although all four modules of study are based on a process-mechanistic analysis of plant response, module 4 places special emphasis on a detailed examination of plant processes. As a result, in addition to open-top chambers it also uses controlled laboratory growth chambers to conduct experiments. The laboratory chambers make it possible to control many environmental conditions (e.g., light, temperature, humidity, nutrient supply to the roots) in addition to air pollutant concentrations. The small size of the laboratory chambers makes it infeasible to grow trees in them. Radishes were chosen to be used with the chambers because of the large body of process information that exists for the species and its relative structural and functional simplicity. The expectation is that given the mechanistic approach being used, the radish results can be related to the behavior of trees and other plants.

Mathematical models are used in the study as both an analytic and an integrative tool. At this early stage of project development, it is not possible to decide whether there is a best modeling approach; hence several approaches are being taken.

The derivation of a general theory is a long-term effort (it will take 5–10 years), but because the experimental design incorporated tree species and stresses that are pertinent to the current concern regarding forest decline, it is anticipated that the results produced periodically over the short term will be of significance.

Geothermal Systems

Removal of Hydrogen Sulfide From Geothermal Steam

by Evan Hughes, Advanced Power Systems Division

Fluids withdrawn from geothermal reservoirs contain dissolved noncondensable gases that flow with the steam when the liquid and vapor phases are separated. These gases reduce the net power obtainable from the steam, and at least two of them, carbon dioxide (CO_2) and hydrogen sulfide (H_2S), are potential corrosives. In addition, H_2S can be an emission control problem. EPRI has developed and tested a process for removing these noncondensable gases upstream of the power plant. Small-scale field tests show that the process has excellent potential for meeting H_2S emission control standards and for reducing acid gases in turbines and condensers. Other benefits could include reduced chemical and maintenance requirements for H_2S abatement, increased plant capacity factor, and simplified condenser design.

Initially, EPRI tested the upstream process at The Geysers, a vapor-dominated (dry steam) field in California. The test established the feasibility of high-efficiency upstream removal of H_2S from geothermal steam (AP-2100). To evaluate the process under conditions typical of the more abundant liquid-dominated (wet steam) geothermal resources, EPRI arranged to conduct additional tests of the same heat exchanger unit at the Cerro Prieto geothermal field in Baja California, Mexico. The objective of the new test program was to map the performance of the process over an extended range of resource and operating conditions. In addition to the test, EPRI evaluated a catalytic reactor as an option for chemical treatment of the removed H_2S gas.

Arrangements for a site and geothermal fluid supply at Cerro Prieto were made by the Instituto de Investigaciones Eléctricas. IIE and EPRI had identified upstream noncondensable gas removal as a subject of mutual interest in geothermal R&D and had entered into an agreement under which they would share the costs of a field test at Cerro Prieto. The Comisión Federal de Electricidad (CFE) provided the site and the geothermal fluid supply, as well as assistance to IIE during installation; IIE conducted the tests and prepared the report (AP-5124).

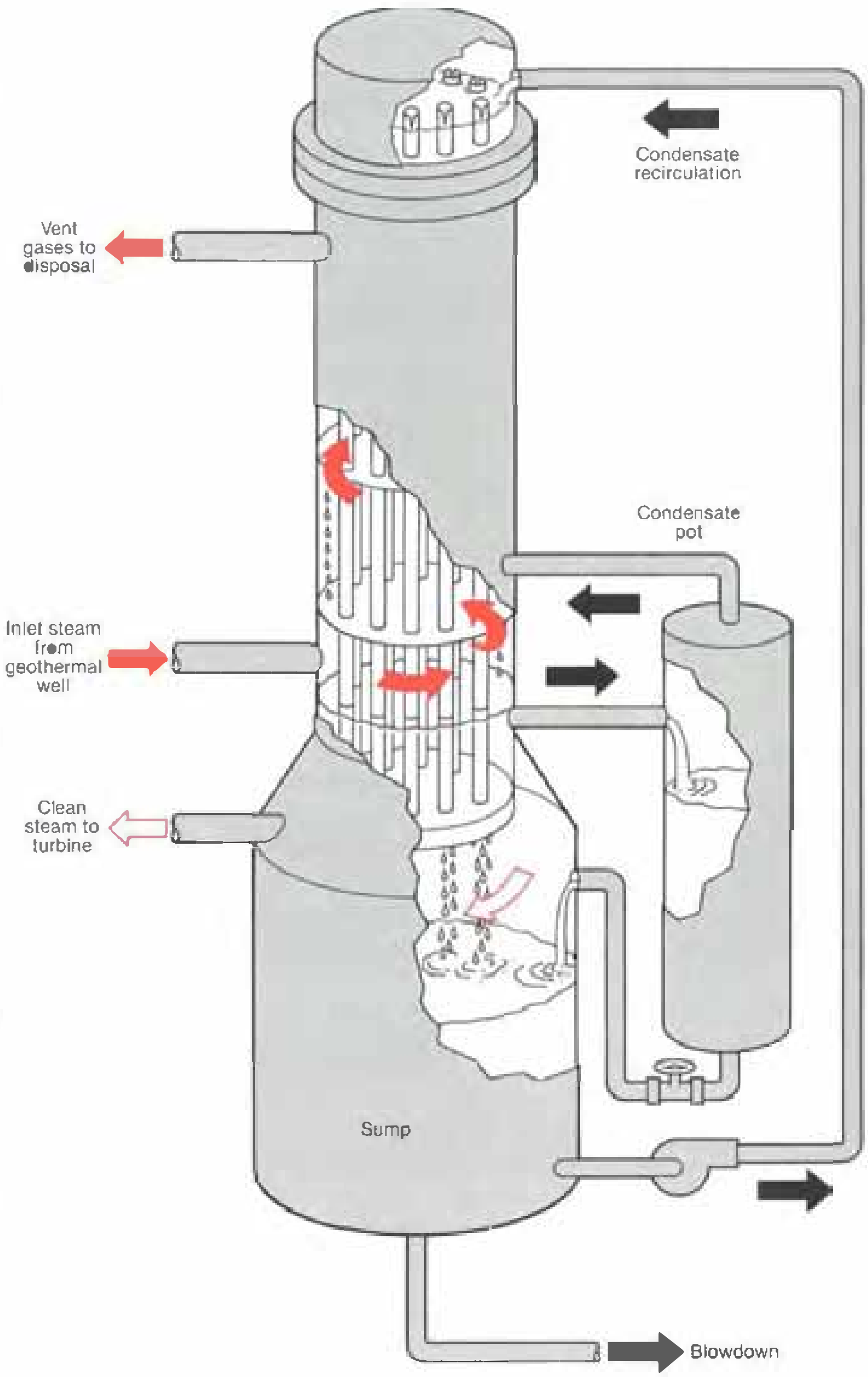
Removing the noncondensables

Figure 1 illustrates the process configuration that was used in both field tests. The process involves condensing and reboiling steam in a shell-and-tube heat exchanger. A vertical tube evaporator is the heat exchanger unit in the configuration shown in the figure. The test unit was designed for a nominal 1000-lb/h (0.13-kg/s) inlet steam flow. The entering geothermal steam is condensed on the shell side of the heat exchanger. About 95% of the noncondensable gases and a small amount (usually 3–7%) of the uncondensed steam flow out from the top of the shell side in a vent stream. In a commercial unit this vent stream would be treated to remove and dispose of the noncondensable gases. A Stretford plant or (as more recently used at The Geysers) an incinerator and scrubber process could be used for such gas treatment. In the Cerro Prieto test a catalytic reactor was used for conversion of H_2S in the vent stream during some test runs. During most of the testing the vent stream was recombined with the clean steam stream after both had been analyzed to determine their H_2S, CO_2, and ammonia (NH_3) content.

Inside the reboiler the condensed geothermal steam flows down the outside walls of the heat exchanger tubes to the bottom of the tube bundle and on through the condensate transfer tank (pot) to the sump. From the sump, condensate is pumped through the recirculation line to the top of the heat exchanger, where it enters the tube side and flows as a film down the inside walls of the tubes. Steam evaporated from the condensate passes downward through the tubes and exits through the clean steam line.

A temperature difference (ΔT) between the shell side and the tube side of the heat exchanger enables heat to flow from the condensing inlet steam to the evaporating clean steam. Saturated temperature and pressure conditions prevail on each side of the heat exchanger because of an equilibrium between the vapor and the liquid water. In the field test the temperature drop between the two sides was varied by changing the corresponding pressure drop. The ΔT was usually kept at about 8°F (4°C) and it ranged from 4 to 20°F (2–11°C). In a commercial unit the design value of ΔT

Figure 1 Reboiler process for removing noncondensable gases (e.g., H_2S, CO_2) from geothermal steam upstream of the turbine. Incoming geothermal steam is condensed and the condensate recirculated to flow downward inside the heat exchanger tubes (tube side). Noncondensable gases in the incoming steam, together with a small amount of uncondensed steam, rise to the top and are vented (shell side). As the condensate flows down through the exchanger tubes, it is reboiled by heat from the incoming steam, and this clean steam, now more than 90% free of noncondensables, is directed to the turbine.



would be selected to optimize process economics; that is, the loss of power associated with a larger ΔT and the consequent production of lower-pressure clean steam would be traded off against the increased cost of using the larger heat exchanger area required for heat transfer at a smaller ΔT.

IIE constructed a steam separator system to supply steam to the reboiler test unit. By using either one or two stages of flashing and separation upstream of the reboiler unit, IIE was able to supply steam at pressures of 1000, 800, and 400 kPa (approximately 140, 115, and 60 psia) and to vary the concentration of noncondensable gases in the steam. Injections of CO_2, H_2S, and NH_3 were used to obtain different mixtures of noncondensable gases.

EPRI's reboiler process can operate with steam at the same temperatures and pressures as produced at the wellheads in geothermal fields, and it does not require chemical treatment of any main flow stream either to or through the power plant. As a result, it is suitable for operation upstream of the turbine, which provides several advantages over processes in which the noncondensables are removed downstream of the turbine.

- The steam flowing to the turbine and condenser is cleaner and less corrosive; thus, reliability should be improved.
- H_2S removed by the upstream process does not get into the turbine condensate, where its removal could require liquid-phase (secondary) treatment to meet plant H_2S emission requirements.
- Removing all noncondensable species, not just H_2S, minimizes the loss of power or steam associated with the ejection of gases from the condenser.
- H_2S can be removed from the steam even during periods when the turbine and generator are inoperative; thus there is no need to close down geothermal wells or to use a separate abatement system to control emissions during those periods.

The advantages to be gained by adding a steam-stripping column to the system were also evaluated in a special test at the Cerro Prieto field. In the steam-stripping column, the condensate produced on the shell side of the reboiler is placed in contact with clean steam, thereby allowing the gases that dissolved in the condensate as it formed on the shell side to return to a vapor stream as the condensate is exposed to the very low partial pressure of these gases in the clean steam routed through the stripper. The steam used for stripping is not lost to the process because it is returned to the reboiler to be condensed along with the main flow of inlet steam through the shell side of the reboiler. In a commercial unit, this stripping column would replace the condensate pot shown in Figure 1. The high-temperature clean steam for the stripper would be produced by compressing a slip stream from the clean-steam discharge.

At Cerro Prieto the basic reboiler system without the stripper was operated at three inlet steam pressures and with various compositions of inlet steam. Such operating parameters as vent rate, recirculation rate, blowdown rate, and pressure drop between the two sides of the reboiler were varied in order to determine how each of them affected reboiler performance. Performance was measured by noncondensable gas removal efficiencies for H_2S, CO_2, and NH_3 and by heat transfer coefficient. The heat trans-

ABSTRACT *Noncondensable gases entrained in geothermal steam can reduce the net power output of geothermal power plants and cause corrosion (H_2S and CO_2) and emission control (H_2S) problems. In an EPRI-developed process, the noncondensable gases are effectively removed upstream of the turbine by first condensing the incoming steam to free the noncondensables and then reboiling the condensate to produce clean steam for the turbine. The noncondensables can then be treated in a separate process or injected back into the geothermal reservoir. Tests at the Cerro Prieto geothermal site in Mexico achieved noncondensable gas removal efficiencies in the range of 92–96% for H_2S and CO_2. Addition of a steam-stripping column increased removal efficiencies to the 97–99% range. A net energy output analysis for Cerro Prieto indicates that a reboiler-equipped plant would have 2–5% more power output than a similar plant with no H_2S abatement system because a 14% steam loss incurred to eject noncondensable gases could be eliminated.*

fer coefficient is the critical parameter in determining the cost of a reboiler unit because it is inversely proportional to the tube surface area required to process the steam flowing through the reboiler to the turbine. In the previous test at The Geysers (AP-2100) the average value of the heat transfer coefficient was approximately 3400 W/(m^2·°C), or 600 Btu/(h·ft^2·°F), with a standard deviation of ± 15%. No effects of operating parameters on heat transfer coefficient were detected at either test site.

Gas removal efficiencies were affected by some of the parameters varied in the tests. The initial test at The Geysers had indicated that the primary effect was that of the vent rate. Vent rate refers to the fraction of actual steam (i.e., water vapor, not including the noncondensable gases) that is vented with the noncondensable gases and therefore is not available as high-pressure clean steam to be sent on to the turbine. (Most of this lost steam could be saved by using it at a lower pressure to drive gas ejectors to remove whatever noncondensable gases and air are present in the condenser.)

The Cerro Prieto tests showed how noncondensable gas removal efficiency is affected by vent rate, inlet pressure, and steam composition. None of the other parameters studied were found to have a measurable effect on the performance of the reboiler. Of the three gas species investigated (H_2S, CO_2, and NH_3), only NH_3 was found to have a significant effect. Higher concentrations of NH_3 decreased noncondensable gas removal efficiency, dropping the H_2S removal efficiency from 94% to 87% as NH_3 concentration in the steam was increased from 100 ppm to over 1000 ppm. However, CO_2 removal efficiency was not affected as much by NH_3 concentration, dropping only from 94% down to 93% or 92% when the NH_3 concentration was increased from 100 to 1000 ppm.

The most significant effect on both H_2S and CO_2 removal efficiencies was that of vent rate. At high vent rates (in the 12–20% range), removal of both H_2S and CO_2 was in the 94.5–96.0% range. However, at low vent rates both gas removal efficiencies dropped to lower values. The size of this drop in efficiency and the vent rate below which a drop in efficiency could be observed depended on the pressure of the inlet steam. The vent rate effect (i.e., the decrease in gas removal efficiency at low vent rates) was more pronounced at high pressure (965 kPa; 140 psia) and less so at low pressure (414 kPa; 60 psia). At the base case pressure (793 kPa, 115 psia), H_2S removal efficiency was 94% at a 6% vent rate and dropped below 92% at a 2% vent rate. The removal of CO_2 was also affected by vent rate and by inlet pressure, but to a lesser extent than H_2S. EPRI's process is not very efficient in removing NH_3 from the steam; measured removal efficiencies were only in the 25–55% range. (It is possible that the NH_3 remaining in the steam will have a beneficial effect by making the steam and condensate less acid and, therefore, less corrosive.) The base case concentrations of the three gases in the inlet steam were 500 ppm, 13,000 ppm, and 100 ppm for H_2S, CO_2, and NH_3, respectively.

Still higher gas removal efficiencies were measured during the recent additional tests at Cerro Prieto in which the steam-stripping column was added to the reboiler test unit. Figure 2 shows the stripping column being installed alongside the reboiler as part of the test system. During the initial series of test runs made with the stripping column in operation, H_2S and CO_2 removal efficiencies in the 97–99% range have been measured. These high efficiencies have been obtained at low vent rates (approximately 3%), thereby showing that a stripper module will enable the upstream reboiler system to achieve high levels of efficiency in removing noncondensable gases while using only a small fraction of the inlet steam in the vent gas stream.

Net power output

The net energy produced by a power plant with the upstream reboiler process, compared with output without the process, is affected by the following.

- Gas ejector gain—the saving of steam resulting from the removal of noncondensable gases upstream and the resulting reduction in gas ejection load at the condenser. (Ejectors, not vacuum pumps, are assumed below because ejectors are used in existing plants at both The Geysers and Cerro Prieto.)
- Vent rate—the decrease in steam flow to the turbine, caused by the venting of some steam along with the noncondensable gases in the vent gas stream.
- Pressure drop—the decrease in pressure and temperature of the steam entering the turbine, caused by the ΔT across the upstream reboiler.

Figure 2 Installation of a steam-stripping column on the reboiler test unit at Cerro Prieto. The original 1000-lb/h upstream H_2S removal test unit is on the right. The stripping module increased removal efficiencies for H_2S and CO_2 to 98% (from 94%). It also prevented the decrease in gas removal efficiency that had previously occurred at low vent rates. The vessel mounted in the frame in the left foreground is a catalytic reactor that was tested earlier in the project. The reactor is a way to treat the vent gas stream, which contains the H_2S removed from the main steam flow. The reactor achieved conversion efficiencies up to 97%, converting H_2S to elemental sulfur and other oxidized species.

▫ Reboiler pumping—the parasitic power required to run the condensate recirculation pump in the reboiler system.

▫ Gas ejector loss—the steam loss resulting from the use of ejectors to remove noncondensable gases from the condenser. (This loss can be eliminated if the vent stream from the reboiler is used to drive the ejectors. In this case, a second-stage reboiler is added to treat the vent stream.)

▫ Turbine output—the difference between power produced by a turbine using pure steam and one using steam containing noncondensable gases. (For practical calculations, gases can be treated as being 100% CO_2. The expanding CO_2 adds power to that produced by the steam alone.)

▫ Backpressure effect—the increase in power output of a turbine exhausting to a condenser at the lower pressure made possible because the reboiler has reduced the noncondensable gas load entering the condenser. (This effect will be zero if the gas ejection with reboiler—"gas ejector loss" above—has been sized to give the same condensing condition as the case without reboiler. Therefore this effect is taken to be zero in the analysis presented below.)

▫ Blowdown—the heat loss in the reboiler that is reflected in the blowdown rate; that is, the fraction of inlet steam ejected as water from the sump and therefore not available to be reboiled to make clean steam for the turbine.

▫ Compressor—the parasitic power required to drive a compressor to recirculate some clean steam as stripping steam if a stripper unit is added to enhance the H_2S removal.

A net power analysis has been performed for the Cerro Prieto conditions. At the site of the Cerro Prieto reboiler tests, the existing power plant has no H_2S abatement system, and 14% of the steam entering the plant from the steam line is used to drive jet ejectors that remove the noncondensable gases from the condenser. To compare the existing unabated plant with a hypothetical plant that uses a reboiler (or reboiler-plus-stripper) system to remove H_2S upstream of the plant, each of the factors listed above was taken into account in a calculation of net power output from a reboiler-equipped plant compared with an unabated plant. Table 1 shows the comparison, first listing the performance, steam supply, and operating characteristics that define the case, and then listing the contribution of each factor that has an effect on the net power output.

Table 1
EFFECTS ON NET POWER
(compared with unabated plant)

Factor	Reboiler Only	Reboiler/ Stripper
Performance		
H_2S removal (%)	95	98
Steam supply		
Line pressure (psia)	90	90
CO_2 content (ppm)	13,000	13,000
Operating parameters		
ΔT drop in reboiler (°F)	8	8
Turbine inlet pressure (psia)	80	80
Vent rate (%)	6	3
Stripper rate (%)	none	4
Net power effects (%)		
Gas ejector gain	+14.0	+14.0
Vent rate	− 6.0	− 3.0
Pressure drop	− 3.0	− 3.0
Reboiler pump	− 0.3	− 0.3
Gas ejector loss	− 1.6	− 1.6
Turbine	− 0.4	− 0.4
Backpressure	0.0	0.0
Blowdown	− 0.5	− 0.5
Compressor	0.0	− 0.6
Total	+ 2.2	+ 4.6

The effects are given in percentage points on the basis of the increase (+) or decrease (−) that would occur relative to an unabated plant.

Compared with The Geysers case considered in AP-2100, the Cerro Prieto case uses more steam to eject noncondensable gases because the gas loading is higher at Cerro Prieto. At The Geysers about 5% of the steam from the line into the plant goes to eject noncondensable gases, which consisted primarily of 3000 ppm CO_2 and 240 ppm H_2S during the EPRI reboiler tests there in 1979 and 1980. At Cerro Prieto the 14% diversion of steam to ejectors handles some 13,000 ppm CO_2 and 500 ppm H_2S that has been present in the steam supplied to the EPRI reboiler tests there. (At both sites the ammonia content has been about the same, some 100 ppm.)

To calculate recirculation pumping requirements in Table 1, the conceptual design for an 18-MW(e) upstream reboiler unit was taken from AP-2100. Mittelhauser Corp. calculated the compressor power requirement for a stripper unit for EPRI as part of RP1197-11, under which Mittelhauser provided equipment and support for the stripper test at Cerro Prieto. It should be noted that the 4% flow shown as stripping steam in Table 1 is not a loss of steam because the stripping steam is returned to the shell side of the reboiler to be condensed and added to the clean steam supply. Hence the power loss associated with the stripper consists primarily of the compressor used to increase the temperature of the approximately 4% of the clean steam that is recirculated to provide clean stripping steam at the shell-side temperature.

The next step

The performance parameters required to support the design of upstream reboiler noncondensable gas removal systems have been established through field measurements over a range of operating conditions. These parameters can now be used to optimize designs and to make cost estimates for upstream noncondensable gas removal systems. Cost estimates developed in the original report (AP-2100) indicated $5.6 million (1979 dollars) for a two-stage upstream reboiler system for a 55-MW(e) plant (1,100,000 lb/h; 139 kg/s steam feed). This was based on a heat transfer coefficient of 3400 W/(m^2·°C), or 600 Btu/(h·ft^2·°F), and a ΔT of 10°F (6°C) across the reboiler. The second stage reboiler was included in order to treat the vent gas stream, thereby making it the source of steam to drive gas ejectors. The total capital and operating costs appeared to be competitive with other H_2S abatement alternatives at the time of the previous report. EPRI plans to use the complete set of performance data in a new design and cost study.

AFBC Evaluation Methods

by Stratos Tavoulareas, Coal Combustion Systems Division

One of the objectives of EPRI's fluidized-bed combustion research is to provide data and tools for utilities to use now in comparing AFBC with other power generation options and later in procuring, constructing, and operating AFBC plants.

During the planning phase, a utility typically compares various power generation options in light of its existing system, future load projections, and other financial and regulatory requirements. The evaluation of each option is usually based on plant-level data, such as plant heat rate, forced-outage rate, capital costs (in dollars per kilowatt), and O&M costs—which are factors in the system-level analysis. The decisions typically made during this planning phase concern the fuel to be burned (coal, natural gas), the technology to be employed (fluidized bed, conventional pulverized coal), the unit dispatch schedule (baseload, cycling, peaking), the number and size of units to be built, and the construction schedule for each unit.

After a technology is selected, the plant configuration is developed through the utility's design specifications, the vendor proposals, and the selection of the best design. The decisions typically made during this phase concern the type and features of the fluidized-bed boiler system to be used and the design margins and premiums for the desired level of fuel flexibility, availability, and operability.

Because fuel availability and prices are likely to change over the course of plant operating life, a utility must be able to estimate the impact of fuel switching on unit performance and operating conditions.

Recognizing these various levels of data and evaluation needs, EPRI's R&D takes advantage of the experience gained from designing and operating AFBC facilities, such as the 1-by-1-ft and 6-by-6-ft bench-scale facilities in Alliance, Ohio; TVA's 20-MW AFBC pilot plant; and the three AFBC demonstration plants operated by Northern States Power, Colorado-Ute, and TVA. A test program was developed for each AFBC facility that provides common test procedures and equipment so that compatibility of the results can be ensured. The data generated from the test programs will be used to create the following data bases and computer codes.

- Data and codes for estimating capital cost requirements and developing construction schedules
- Performance data (e.g., reliability, efficiency, O&M costs, emissions)
- A design evaluation methodology (AFBVAL code) for calculating the trade-offs and benefits of various design options on the basis of a consistent set of technical and economic assumptions
- Data on the performance of various fuels in an AFBC boiler and a means of estimating the performance impact of switching fuels for a given design (FBCBAL code)

ABSTRACT *Electric utilities are considering a number of options for meeting anticipated load growth. These options include building new units and revitalizing obsolescent plants by using new technologies, such as gasification–combined-cycle and fluidized-bed combustion. However, equipment vendors, architect-engineers, and EPRI's member utilities need hands-on experience with these new technologies, as they differ significantly from those used in conventional plants. To help bridge this experience gap, EPRI is developing technology transfer tools and other aids based on the experience gained in the design, construction, testing, and commercial operation of three atmospheric fluidized-bed combustion (AFBC) demonstration plants. Computer codes are one tool utilities can use to optimize AFBC plant design, minimize project risks, and fully exploit the fuel flexibility of AFBC systems.*

Cost estimation and construction schedules

During technology option screening (generation expansion planning) and later during evaluation of alternative AFBC plant designs, utilities need to make capital cost estimates and determine the project scheduling requirements for each design option. To address these needs, EPRI is developing cost estimates for generic AFBC plants and a methodology that makes it possible to estimate capital requirements for site-specific design specifications/assumptions, and is monitoring and documenting costs and construction activities at the AFBC demonstration projects.

In the past, EPRI completed design evaluation studies that developed such cost estimates mainly for R&D funding allocation and for planning and evaluation of the AFBC demonstration projects. One of these studies compared alternative AFBC steam generator designs (CS-5296). Under the same project, a Lotus 1-2-3–based model was developed that performs mass balances around AFBC systems and calculates resource requirements, capital requirements, and busbar cost. Similar studies are under way to compare AFBC designs with other coal-fired technologies (RP1180). With early deployment of AFBC at the three utility demonstrations, however, there is an opportunity to gather data from operating plants that reflect actual costs rather than estimates. The availability of such data will reduce the uncertainty associated with future AFBC cost estimates.

EPRI is monitoring and documenting both capital costs and O&M costs at the three demonstration plants (RP2628, RP2683). Capital cost monitoring requires a consistent level of detail among the three projects and a strong link between cost elements, on the one hand, and equipment specification and performance, on the other. The first element (consistency) is accomplished by a detailed accounting system developed by EPRI and used in all demonstration projects. The second link between cost and equipment specification/performance is made possible through the CDMS (cost data management system), a software package that can accept complex cost account structures and equipment descriptions. The latter include design specifications, expected performance, design conditions, and other factors affecting the cost of each plant component.

The cost estimates from the projects described above will provide the data for developing a cost-estimating procedure (RP2303) to be used by electric utilities during the early stages of AFBC projects (technology option screening and evaluation of AFBC boiler design alternatives). This procedure will generate capital cost requirements based on such parameters as unit size, scope, financial factors, and site specific requirements. In addition, first-year O&M costs and levelized busbar costs will also be calculated.

Two versions of the procedure will be available. The simplified version will provide rough cost estimates and can be used for technology screening. The detailed version will be based on preliminary plant layout and can be used for AFBC design configuration comparison; it can also be used in conjunction with the AFBVAL code for more-detailed design evaluation.

In addition to capital cost requirements for the AFBC demonstration projects, other engineering- and construction-related activities are being monitored and documented. Reports will be published on the origin of each project (e.g., feasibility studies, design studies, laboratory/small-scale testing, equipment bid evaluation, financing), demolition and relocation, and construction (including detailed schedules).

These reports, together with the equipment design report, will provide a complete record of the AFBC demonstration projects and can be used by other utilities as an aid in planning AFBC projects.

Plant performance and reliability analysis

Extensive test programs will be carried out at the three AFBC demonstration plants to characterize their performance and document O&M requirements. Performance characterization will include boiler efficiency, emissions, dynamic response characteristics, and component reliability. Such information can be used for AFBC design evaluation purposes.

Prediction of the reliability, availability, and maintainability (RAM) of a plant is becoming increasingly important to utilities. Such an evaluation requires a RAM model, component failure data, and repair data. Reliability computations can be performed with RAM computer codes, such as UNIRAM. The component reliability data, mean time to repair and mean time to failure, however, are usually the key elements in reliability analyses.

In the case of a conventional power generation technology, the ideal data base on component maintainability is usually the one the utility has developed for its own system because it reflects the actual operating conditions, operating and maintenance policies, environment, and so on. Other sources of reliability data include the generating availability data system (GADS) of the North American Electric Reliability Council and the equipment vendors. In the case of a new technology such as AFBC, however, with new process characteristics and unique design of certain components, the existing data bases cannot provide the required information.

To address this need, EPRI has developed a plan to monitor the reliability of TVA's 20-MW pilot plant and the three AFBC demonstration plants (RP2303). A number of alternatives were considered before selecting the data-gathering system that is being used. The main objective was to develop a method that would provide the most data with the least additional work for plant personnel. The system selected is based on the maintenance work request system already used by the host utilities in their day-to-day functions. The data monitored include component operating conditions, name plate data, a description of the problem, the action taken to correct the problem, the time of the failure and time to repair, and the materials required for repair.

The raw data will be gathered so that reports can be generated and used in such areas as the following.

- Future AFBC plant design evaluation and optimization
- Evaluation of life extension work on specific equipment
- Preventive maintenance planning
- Identification of causes of the most significant failures
- Development of R&D programs for reliability improvement

Integrated engineering and financial analysis

During the design selection process, the objective is to determine and select the design alternative that maximizes the excess benefits (revenues from electricity generation) over costs (capital, annual fuel, and O&M costs) to the utility. To address this need, EPRI is developing a family of computer codes (AFBTREE) that can be used for scoping studies, competitive bid evaluations, and AFBC plant design optimization. AFBVAL, the first of the AFBTREE programs, performs integrated engineering and financial evaluations at the unit level. Engineering computations yield mass balance, boiler efficiency, and annual consumption and production. Financial computations by the revenue requirements method yield O&M costs, fuel and consumable expenses, schedule opportunity costs (AFUDC), and fixed-cost carrying charges. Benefits can then be calculated on the basis of the value of electricity and unit availability.

In addition to capital cost data, AFBVAL input includes timing factors (e.g., construction schedule, year placed in service, usable life), economic factors (e.g., prices of consumables and electricity produced, escalation rates, and utility financial structure), plant availability, O&M labor costs, AFBC process factors (e.g., excess air, sulfur capture efficiency), and coal and limestone analyses.

Equivalent plant availability or capacity factor can be provided by the analyst or calculated on the basis of design configuration and component reliability data (mean time to failure and mean time to repair). Benefits to the utility from the AFBC capacity addition being considered can be calculated on a system basis by using the effective load-carrying capability of the unit to reflect unit availability and utility system characteristics (the Garver methodology).

AFBVAL can be used for generating single-point estimates of the net benefits from each alternative AFBC plant design. Further, it can be used for sensitivity and scenario analyses to assess the effects of different technical and economic factors on power plant economics. An example of such an evaluation is the comparison of alternative coal-drying designs for a 160-MW AFBC plant. The following were the designs considered.

- Design 1. Uses separate coal and limestone feed systems and a coal dryer.
- Designs 2 and 3. Use fly ash to dry the coal, therefore eliminating the need for a coal dryer. In addition, these designs combine the coal with the sorbent (unified feed), which further simplifies the plant. The only differences between design 2 and design 3 were the engineering costs and the construction schedule.

To evaluate these design alternatives, AFBVAL was used. Originally the base-case file was set up for design 1. Relative to the base case, implementation of designs 2 and 3 was expected to affect the performance of the unit, plant availability, process capital, auxiliary power requirements, maintenance costs, and construction schedule. Following adjustment of the AFBVAL input, life-cycle benefits (expressed in 1985 dollars) were estimated for each design: for design 1, the benefits were $104 million; for design 2, $72 million; and for design 3, $109 million.

The benefits from each design alternative indicate that the unified feed system is preferred over the base-case design. The second alternative (design 2) is a special case and reflects the effects of project schedule extension and reengineering costs caused by incorporation of this concept after the construction had started and the engineering work had been completed. Such information provided by AFBVAL can be used by design engineers to optimize the configuration of the plant and by utility engineers for boiler bid evaluation and design improvement.

Following development of a base case, a number of variables (up to 20 AFBVAL inputs) can be selected for sensitivity analysis. This is particularly important in the case of uncertain variables, evaluation of which identifies the ones with the most impact on power plant economics. For instance, in the previous example the impact of alternative values for seven variables was assessed. Total plant costs, operating year, and capacity factor (plant availability) proved to have the most significant impact on net benefits. Identification of such important variables makes it possible to direct improvements to the area where the expected payback is higher.

Scenario analysis can also be used for evaluating changes in more than one variable at a time. (AFBVAL accepts up to 100 scenarios.) Such a capability can be used to generate probability distributions for each plant design considered (Figure 1).

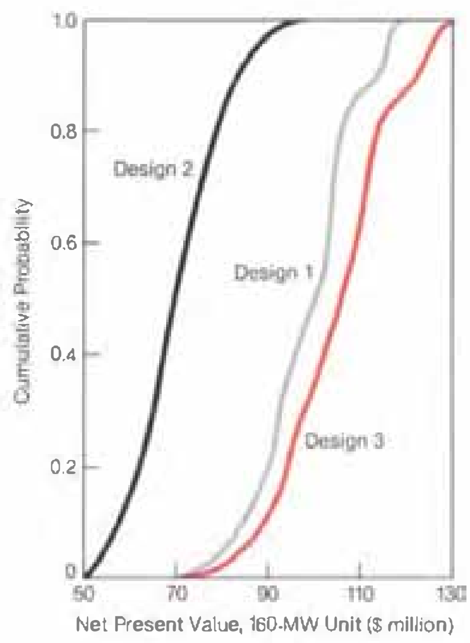
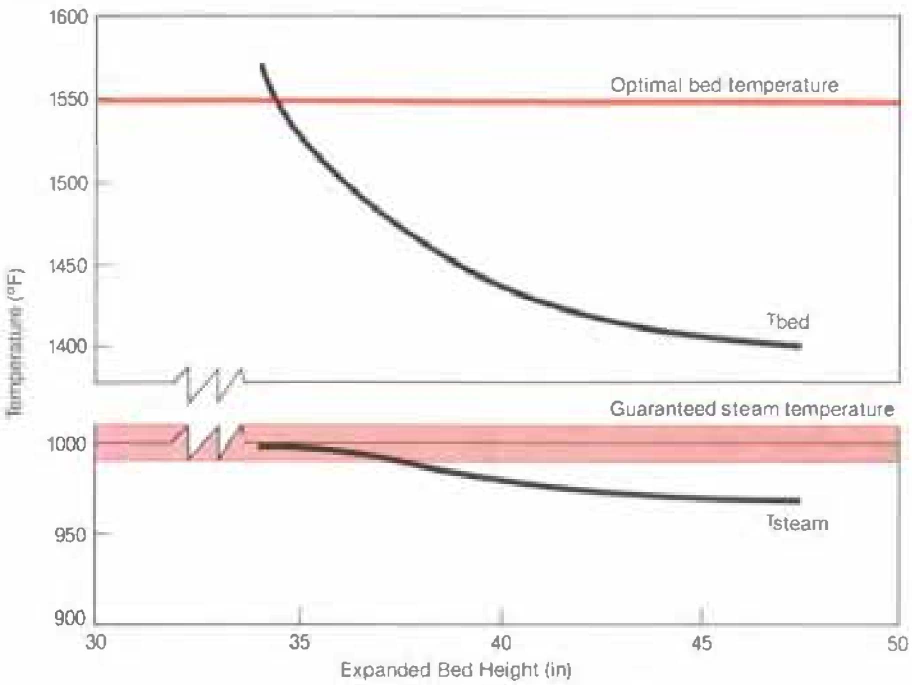


Figure 1 Value distributions for a 160-MW AFBC plant, indicating a base case design (design 1), a unified feed alternative in a retrofit project (design 2), and a unified feed alternative in a new plant (design 3).

Figure 2 FBCBAL code was used to evaluate the performance of a utility AFBC boiler firing the design fuel under different operating conditions. A reduction in the expanded bed height was necessary to increase the bed temperature and achieve the guaranteed steam temperature. The optimal bed temperature is shown in gray. This figure shows the effect of the bed temperature on the steam temperature in relation to bed height for the considered boiler design.



For seven uncertain variables, each of which has three values, there are more than 2000 possible scenarios. In the previous example, AFBVAL was used to analyze all these scenarios, and the results were then plotted as the cumulative probability versus net present value. For a certain level of benefits, each curve shows the probability that the actual net present value will be less than that level.

Similar analyses can be performed to optimize a given AFBC plant design. In most cases, evaluation of a design change involves a trade-off between increased benefits and expenses. AFBVAL can be used to calculate the net benefits for each design change and to reveal the best design. AFBVAL output can also be used as production cost model input to assess the benefit of each design to the utility system. Decision Focus, Inc., developed AFBVAL under RP2543 and RP2303, and it is available for mainframe and IBM PC–compatible computers. The prerelease version of AFBVAL was successfully used by member utilities, such as Wisconsin Electric Power, Potomac Electric Power, Consolidated Edison, and Virginia Power. The production version will be available by February 1988.

Plant performance assessment

To evaluate the performance of AFBC plant designs, EPRI is developing the FBCBAL code (RP2303), which performs energy and material balances for AFBC boiler designs. The code will be available for IBM PC–compatible computers and will accommodate any AFBC plant configuration.

FBCBAL is supported by four main input files—an AFBC boiler configuration data file, a fuel data file, a limestone data file, and an operation data file. Because each of these data files is independent, different fuels, sorbents, and operating conditions can be studied for the same design configuration. The fuel data file contains fuel-specific parameters that enable FBCBAL to predict boiler performance for a given fuel. The parameters included in this file are fuel chemical composition, size distribution, char reactivity, and other fuel properties. The final version of the code will include a library of files for a variety of fuels that have been tested at different AFBC facilities (such as the facilities in Alliance, Ohio, and TVA's 20-MW pilot plant). It is expected that the first release of the code will include Kentucky No. 9 coal, Pittsburgh No. 8 coal, Sarpy Creek (Montana) coal, and North Dakota lignite.

The FBCBAL code can be used at various points in an AFBC project from its inception to plant operation. The primary use of the code is the evaluation of AFBC plant performance under different operating conditions. During plant operation, the utility will be able to assess the impact of fuel switching on the performance of the AFBC boiler before committing to a fuel purchase. To do this, the utility (after adjusting the boiler configuration file to match the design parameters of the AFBC boiler of interest) can search the fuel data file to see if a sample of the same coal seam has been tested, in which case FBCBAL can be used without modification. If the fuel is not included in the data file, a fuel sample can be tested according to the EPRI fuel characterization methods and the results placed into the FBCBAL data file. Subsequently the utility can predict AFBC plant performance under a variety of operating conditions for all the fuels included in the data base.

Similarly, FBCBAL can be used for low-load performance analysis and AFBC plant design evaluation (in conjunction with AFBVAL). Other possible applications of the code are the generation of preliminary mass and energy balances for development of design specifications (using a generic AFBC plant design), on-line monitoring and performance optimization, and the tuning of controller settings at different loads.

A recent study conducted to evaluate the performance of an actual utility AFBC boiler provides an example of FBCBAL's applications. The study predicted the performance of the boiler when it fired the design fuel over a range of operating conditions. During a set of such computer runs, the expanded bed height was varied (design point: 48 in) to investigate its effect on bed temperature and steam outlet conditions. Figure 2 demonstrates that reduced bed height was required to meet guaranteed steam temperature. This limitation was determined to be caused by in-bed tube oversurfacing. Although the boiler can operate under these conditions (reduced bed level), such operation will adversely affect the control operating range. Design adjustments can be made prior to startup of new units, thus avoiding any negative consequences. Similar analyses can be performed for part-load operation of a given boiler and performance with alternative fuels.

Nuclear Plant Safety

Steam Generator Tube Rupture

by James Lang, Nuclear Power Division

The principal safety concern about steam generators in pressurized water reactors is the effect of tube rupture on public health and safety. Most of the research sponsored by EPRI and the Steam Generator Owners Group has addressed steam generator reliability and the detection, correction, and prevention of conditions that could result in tube rupture. This work has shown that careful maintenance of secondary water chemistry minimizes tube attack in steam generators. Moreover, routine nondestructive examination (NDE) of steam generator tubes with the eddy-current technique can detect widespread attack, locate many defects before they leak, and monitor the progression of such defects. Use of fiber-optic scopes and small television cameras can effectively detect some of the conditions that lead to tube wear. Other work is under way to define the conditions that cause flow-induced vibration of tubes or components that come in contact with tubes, the objective being to prevent or correct tube fretting and wear. EPRI has also completed work to minimize the impact of the few tube ruptures that may occur. The Nuclear Safety Analysis Center (NSAC) has done analytic work (RP2420); the Safety Technology Dept. of EPRI's Nuclear Power Division has sponsored the experiments (RP1845).

ABSTRACT *EPRI has sponsored research to detect, correct, and prevent conditions in pressurized water reactors that could cause steam generator tube rupture. Researchers have developed methods for detecting flaws that might grow to critical sizes, for reducing tube susceptibility, and for minimizing the impact of actual tube rupture. In addition, EPRI has developed computer codes for modeling mechanisms of crack growth, determining flaw size, and calculating reactor core cooling under transient conditions caused by hypothetical tube ruptures.*

Leak before break

Leak before break means that a flaw in a tube will produce a detectable primary side–secondary side leak before the flaw grows to a critical size that could rupture the tube. Once a leak is detected, plant operators can act to avoid rupture.

One large class of leak-before-break defects is well understood. This class consists of deep, small-volume defects, such as pits or local wastage. However, the leak-before-break phenomenon does not apply to a smaller class, which consists of deep but very large volume defects, such as large wear scars and wastage over a large area. These types of defects have caused most of the tube ruptures, but they are amenable to detection by NDE and corrective action. EPRI's leak-before-break research, therefore, has focused on cracks that are difficult to detect and size by NDE techniques and difficult to prevent. Researchers have developed generalized methods for calculating leak-before-break margins that are carried out in two parts: (1) critical crack lengths and leak rates, and (2) crack growth rates to determine margins.

EPRI developed a computer code, PICEP, for calculating critical crack lengths (i.e., the length of a crack that could result in rupture), and primary-to-secondary leak rates for stainless steel pipes and alloy 600 (Inconel) steam generator tubes. PICEP calculates both leak rates and critical crack lengths for the appropriate tube material, tube size, crack geometry, and loads (NP-3596-SR). The code calculates the critical length of circumferential and axial cracks and leak flow on the basis of EPRI's modified version of Henry's homogeneous nonequilibrium critical flow model. In addition, users can vary assumed crack shape, roughness, and the number of turns in the leak flow path to better model cracks.

The rates at which cracks grow are calculated by taking into consideration the predominant mechanisms of crack propagation. Once-through steam generators used in Babcock & Wilcox (B&W) plants are straight-tube designs. Differences in the thermal expansion of tubes and shells during some transients and modes of operation create axial loads on the tubes, and these loads may produce circumferential cracks. In fact, cracks that have developed in once-through steam generators have been predominantly circumferential and have had a morphology suggesting fatigue as the dominant method of crack propagation.

Recirculating steam generators, the types used in Westinghouse Electric and Combustion Engineering plants, are U-tube designs in which both inlet and outlet ends of the tubes are anchored to a single tubesheet. To minimize axial loads, the tubes are not axially restrained. Temperature differences between the inlets and outlets give rise to bending moments in the U-bends, but internal tube pressure creates dominant tube loads in the hoop direction. Consistent with such loading, the predominant orientation of cracks in tubes of recirculating steam generators has been axial, and the cracks have been attributed to stress corrosion.

Researchers analyzed two representative cases: a once-through steam generator and a recirculating steam generator. They applied the dominant crack growth mechanisms to demonstrate the technique and to calculate generic trends. The analyses showed that for once-through steam generators circumferential cracks in tubes under axial tension would tend to grow through the wall and leak before they grew around the circumference. Figure 1 shows typical leak-before-break margins for both once-through steam generators and recirculating steam generators. In both cases, detectable primary-to-secondary leakage provides some margin between leak detection and growth of a crack to a critical length.

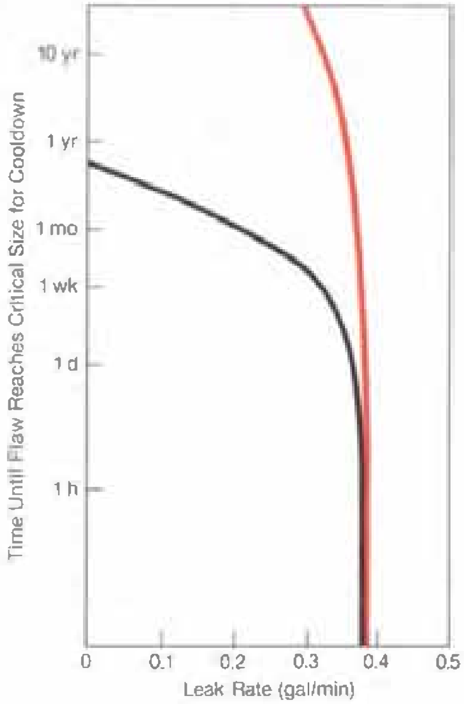
Core cooling

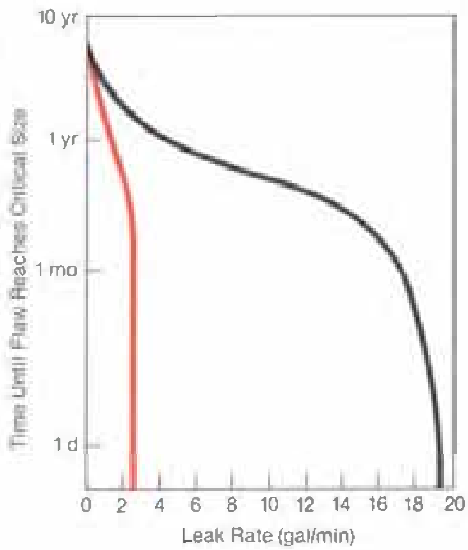
Steam generator tube ruptures that have occurred in the Prairie Island-1 and Ginna plants and tube rupture experiments at the semiscale and model boiler (MB-2) facilities have provided data for verifying the system thermal and hydraulic codes RETRAN and RELAP, as well as vendor codes used for licensing. These codes, in turn, have been applied to calculate the responses of plants to postulated steam generator tube rupture events.

Researchers evaluated the effects on core cooling of tube ruptures in one or both steam generators of a B&W plant during a large-break loss-of-coolant accident (NSAC-72). They used the RELAP4/MOD7 computer code to calculate the peak fuel cladding temperatures reached during the LOCA transient, assuming varying numbers of ruptured tubes (up to 300) in each steam generator. Analyses show that a B&W-designed pressurized water reactor maintains satisfactory core cooling when tubes rupture in conjunction with a design-basis LOCA. Figure 2 shows the calculated peak cladding temperature versus the number of ruptured tubes. The maximum fuel cladding temperature was calculated to be 1605°F (871°C), well below the licensing limit of 2200°F (1204°C). Moreover, the calculations revealed no strong relationship between the maximum fuel cladding temperature and the number of tubes assumed to have been ruptured in each steam generator.

Other analyses assessed the system response of a lower-loop B&W plant to the rupture of single or multiple tubes in one or both once-through steam generators (NSAC-101). Investigators used the RELAP5 computer code for their calculations of the rupture of a single tube in steam generator A, the rupture of 10 tubes in generator A, and the si-

Figure 1 **(a) Time to reach critical flaw size for cooldown by fatigue loading at full power with flow-induced vibration is plotted against the detectable leak rate for a once-through steam generator. Assumptions: There is a threshold stress below which flaws do not grow (color); and all stresses cause flaws to grow (black). This graph is not applicable if stress corrosion cracking or corrosion-assisted fatigue occurs. (b) The remaining life for main steam line break (color) and for steady-state operation (black) is plotted against the detectable leak rate for a recirculating (U-tube) steam generator.**





multaneous rupture of 5 tubes in generator A and 5 tubes in generator B. In addition, personnel repeated some analyses to assess the effect of continued reactor coolant pump operation on plant response during the transient.

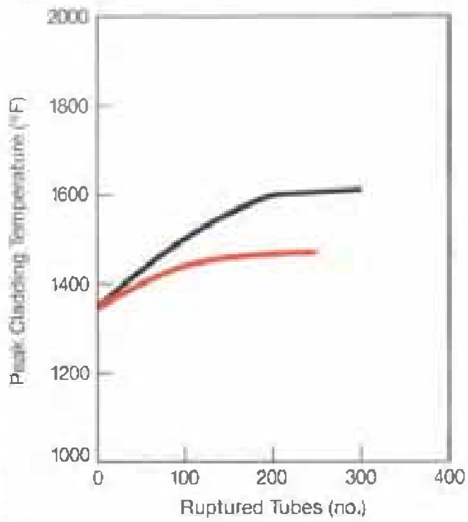
Results show that core cooling was maintained for all cases; that is, no fuel rod cladding temperature excursions were calculated in any of the cases. In all cases, a controlled shutdown was achieved. Primary pressure was below the lowest secondary safety valve opening set point and continued to decrease; hot leg subcooling margins were greater than 20°F (−6.7°C). Both forced circulation and pressurizer spray were available when reactor coolant pumps continued to operate during the postrupture transient. The plant recovery was calculated to be steadier and more easily controlled than if the pumps were tripped early in the transient. If the reactor coolant pumps were tripped, natural circulation and/or feed and bleed were sufficient to cool the plant. Researchers modeled a Westinghouse-designed two-loop plant with RETRAN (NSAC-77) and similar transient cases with similar results.

Radiation release

EPRI has sponsored research both on developing analytic techniques for calculating radiation release during a steam generator tube rupture event with existing information and on determining experimentally the attenuation that occurs when radionuclides are transported through steam generators from primary to secondary leaks.

To address the problem of radionuclide release from a tube rupture in a once-through steam generator, investigators modeled the basic processes of flashing at the leak and evaporation on heated tubes. Calculations for various tube rupture transients yielded average steam generator decontamination factors (DFs) several times greater than the values of 1 or 2 used in other analyses. Figure 3 is a plot of DF versus time for the rupture of a single tube in a once-through-steam generator, assuming constant steaming of the affected generator. The model has been extended to recirculating steam generators. The DFs calculated for the rupture of a single tube in a recirculating steam generator range from 700 to >10,000 during the transient. A DF of 100 has been used commonly in other analyses.

Figure 2 **Peak fuel cladding temperature is plotted against the number of ruptured tubes: ruptures in one steam generator (color) and ruptures in both steam generators (black) for a B&W once-through steam generator.**



The bulk of EPRI's work in radiation release has been experimental. Small-scale and fluid-modeling experiments have been supplemented by running a selected test matrix in a prototypical model boiler test facility in a cooperative effort with NRC, Westinghouse, and, in part, the Central Electricity Generating Board (England).

The MB-2 test facility (NP-3494) is an approximately 1% power-scaled model of the Westinghouse Model F steam generator. It is designed to be geometrically and thermohydraulically similar to the prototype steam generator and is capable of generating a maximum of 10 MW (th) power. The MB-2 contains a tube bundle (52 tubes) 22 ft high (6.7 m). The model boiler components are housed inside a pressure vessel 50 ft high (15 m) with an inner diameter of 32 in (81 cm). Researchers have conducted a series of transient tests of the following events with this test model (NP-4786).

- Loss of feedwater
- Steam line break
- Steam generator tube rupture
- Activity transport following rupture

Using the results, personnel refined the experimental technique and carried out a series of additional tests. Separate chemical tracers were used in the primary and secondary coolants of MB-2 to determine moisture carryover and the fraction originating from the primary side during a simulated double-ended guillotine rupture of a tube. Data from these tests show steam generator partition factors one to several orders of magnitude higher than assumed in current design basis calculations, even for events beyond the design basis.

Achievements

Work being conducted by EPRI and others has produced a body of knowledge that may alleviate the concern about effects of steam generator tube rupture on public health and safety.

- Careful maintenance of secondary water chemistry minimizes tube attack in steam generators.
- Routine NDE of steam generators can detect widespread tube attack, monitor the progression of such attack, and detect

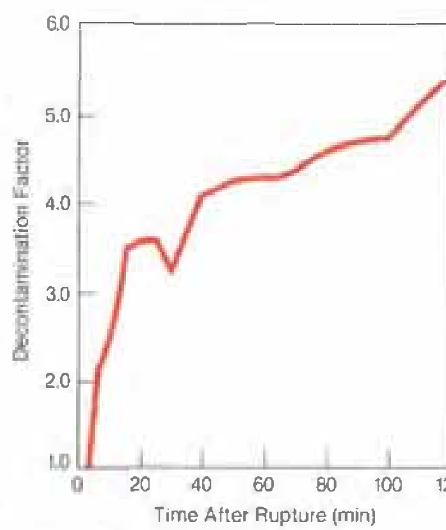


Figure 3 **Decontamination factor is plotted against the time after rupture of a single tube for a B&W once-through steam generator.**

many mechanical and corrosion-induced defects before they leak.

▪ Most tube defects, including cracks difficult to detect by NDE techniques, will leak detectably before they break.

▪ Even if more than one tube ruptures in a steam generator, plant recovery can be handled by using emergency procedures without loss of core cooling.

▪ Analysis and experiments are yielding steam generator partition factors or DFs much larger than those assumed in design basis calculations. Best-estimate analyses thus show even multiple tube ruptures need not cause high radiation dose rates.

Combined-Cycle Plants

Gas Turbine Heat Recovery

by Henry Schreiber, Advanced Power Systems Division

ABSTRACT *A new design for heat recovery steam generators (HRSGs) may overcome operating and maintenance problems of earlier types. A current test of a demonstration module of this HRSG at a utility site was interrupted by problems unrelated to the test. Subsequent testing of the HRSG at the site required a new test plan. Early results are promising. Final results and a report are expected by mid 1988.*

In the late 1960s and early 1970s numerous combined-cycle generating units were placed in service. These units typically consisted of combustion turbine generator sets that vented high-temperature turbine exhaust gas into drum-type HRSGs. The resulting steam from one or more HRSGs was then used to power a steam turbine generator. Combustion turbine vendors sold many of these early units as a package, which included the turbines, HRSGs, and often, the balance of the plant. Operating and maintenance problems in some of the early HRSGs prompted EPRI's interest in an all-stainless-steel, once-through HRSG being developed by Solar Turbines for naval applications.

In 1979 EPRI funded a short report by Solar Turbines, which describes the technology of this new HRSG. The design concept promised sufficient potential operating and maintenance advantages to warrant EPRI's cofunding a field test to demonstrate operability, controllability, and durability under utility operating conditions.

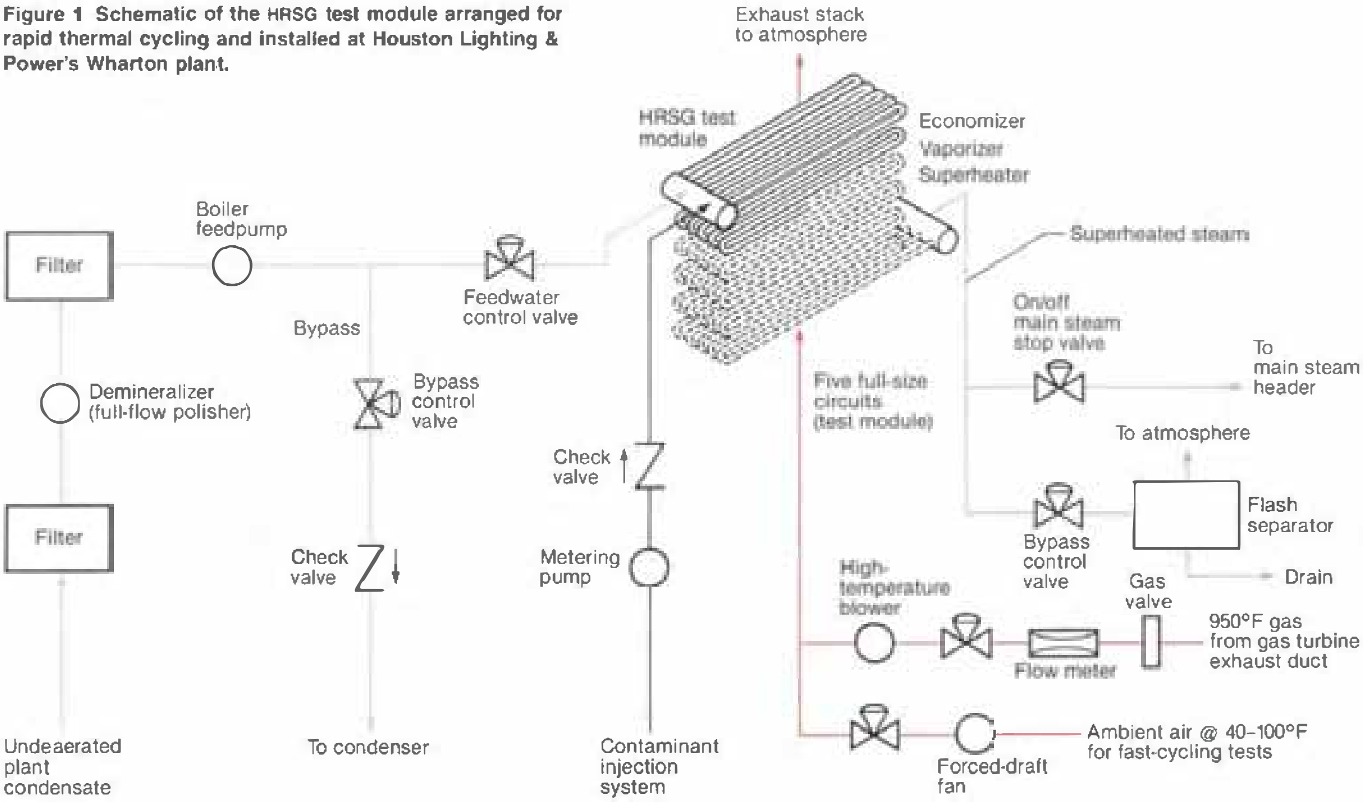
Under contract with EPRI, Solar Turbines designed a 5-tube HRSG module, using tubes of the size that would appear in a full-size 48-tube HRSG. It has a capacity of 6000 lb/h superheated steam at 820 psig (5.8 MPa) and 840°F (449°C), which matches the host utility's HRSG steam discharge conditions. Under contract to Solar Turbines, Bechtel Power designed the balance-of-plant installation. Houston Lighting & Power offered to serve as the host utility. Arinc Research studied the technical aspects of using alloy 800 for HRSG tubing.

The field test HRSG module was installed adjacent to Unit 41 at Houston Lighting & Power's T. H. Wharton plant. Unit 41 is a General Electric MS7001-B combustion turbine, which exhausts into its own HRSG, also of General Electric design. This and three other identical units provide steam for one nonreheat steam turbine.

Figure 1 is a schematic of the test setup. A constant-speed high-temperature blower with a variable inlet vane extracts combustion products at 950°F (510°C) (baseload) from a point in the gas turbine exhaust duct upstream of the first HRSG heat transfer surface. The blower forces the hot gas through the test module and then to a separate exhaust stack. Undeaerated plant condensate from the hot well is full-flow polished to a solids level of less than 20 ppb and is fed to the test module by a constant-speed boiler feedpump. Feedwater flow rate is controlled by a modulating bypass valve arrangement.

The once-through HRSG has horizontal tubes arranged in a serpentine pattern so as to be self-draining by gravity. Feedwater enters each of the five tube circuits in the test module through fixed metering orifices to promote equal flow and stability in the five parallel paths. As Figure 1 shows, the test HRSG acts like a variable geometry device in that the section of each circuit that acts as economizer, evaporator, and superheater depends on the feedwater flow rate, the gas flow rate, and the temperatures and pressures in the system. There is no radiant heat transfer section. Steam discharge pressure is determined by the main steam header pressure. Steam discharge temperature is determined by controlling feedwater throughput rate. In a full-size unit, a micro-

Figure 1 Schematic of the HRSG test module arranged for rapid thermal cycling and installed at Houston Lighting & Power's Wharton plant.



processor uses combustion turbine gas mass flow and exhaust gas temperature to set feedwater flow rate in a predictive (feed forward) control loop. A closed loop control circuit trims feedwater flow rate to provide precise control of superheater steam outlet temperature. The unit is designed to operate without a gas bypass duct, as it is capable of hot, dry operation in an unfired mode. The HRSG casing is internally insulated so the casing structure stays cold when running. Figure 2 shows the site installation.

The original test plan called for Unit 41 to run as a baseload unit for two years or 12,000 hours of operation, during which one of the five circuits would be segregated and subjected to accelerated aging by injection of feedwater contaminants and thermal cycling. Tube samples were to be cut out at intervals to monitor metal condition, corrosion indications, and possible failure mechanisms. The steam from the remaining four boiler circuits was to be fed to the Unit 41 HRSG discharge at the same conditions that exist in the main steam header.

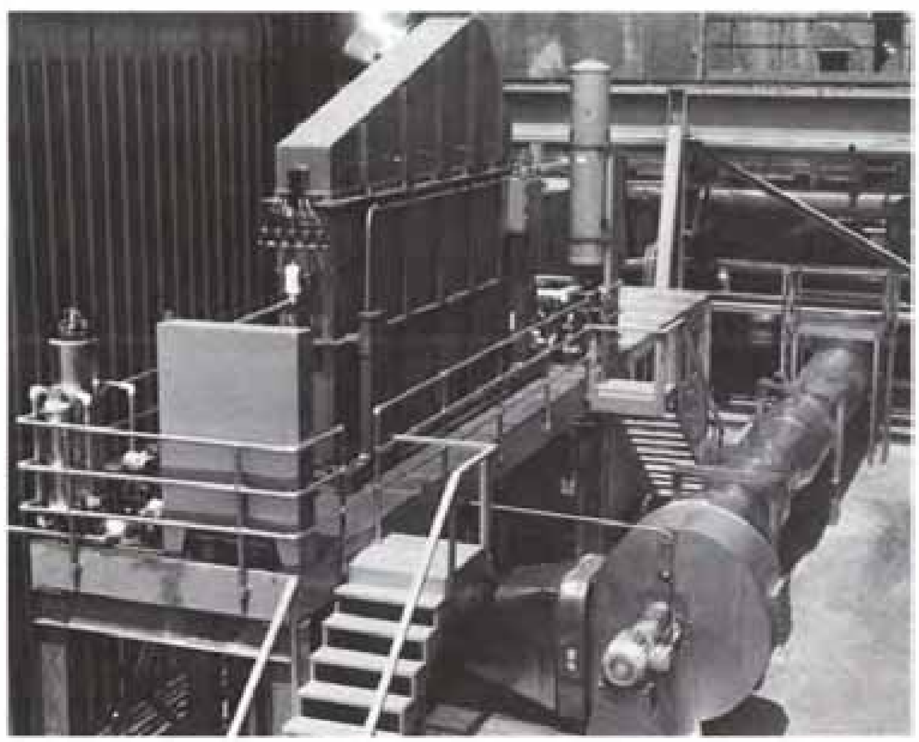


Figure 2 Once-through alloy steel HRSG test module developed by Solar Turbines. The module has a capacity of 6000 lb/h superheated steam at 820 psig and 840°F.

The test unit started up with all five circuits generating usable steam before installation of the single-circuit failure acceleration equipment. After a short breaking-in period, the test unit ran successfully on automatic control for more than 450 hours and experienced 40 starts. During this run, the test unit operated stably and followed gas turbine operating conditions. Steam temperature was controllable to ±5°F of the set point. A forced outage on Unit 41 unrelated to this test suspended testing. When Unit 41 started again, dispatch requirements dictated it be cycled. In this operating mode, the unit ran only a few hours a day, if at all, and it became apparent that the originally conceived 12,000-hour test could not be completed within a reasonable time and cost. A new test plan was formulated to thermally cycle the whole unit rapidly, as well as to contaminate the feedwater, thus simulating a failed condensate polisher during a condenser cooling-water leak. The purpose was to age the unit as quickly as possible by subjecting it to the severest service condition.

The test arrangement was modified to alternately flow hot gas turbine exhaust gas and cold ambient air through the test HRSG. A chemical system to feed condensate contaminants was added. Controls were modified to permit automatic cycling. The steam from the test HRSG, no longer suitable for introduction into the main steam header, was vented through a flash separator.

This new test is expected to be completed in mid 1988, with a final report to be published in late 1988. An independent study by Arinc Research Corp. on alloy 800 as an HRSG tube material will be the subject of a separate report. Meanwhile, two commercial HRSGs of this design have each operated more than 35,000 hours at a natural gas processing station in Okarche, Oklahoma, with an availability of over 99%. Tube samples taken from one of these units after 9000 hours of natural gas firing show no signs of distress. Twelve more units are currently being installed in small power generation facilities at industrial plants.

The corrosion-resistant properties of the alloy 800 boiler tubes and 409 stainless steel fins, together with the simplified feedwater and steam circuitry of this design, offer a promising breakthrough to more reliable, low-maintenance HRSG operation. The absence of steam drums permits very rapid startup of this type of unit and eliminates trips that result from drum level excursions during starts or rapid load changes.

Coal Economics

CO_2 Production in Gasification-Combined-Cycle Plants

by Bert Louks, Advanced Power Systems Division

Before recent declines in crude oil prices, CO_2 was a valuable commodity in the petroleum industry. When injected into oil formations under certain conditions, CO_2 becomes miscible with the oil. The oil's viscosity is lowered, thereby making it possible to recover more oil.

When crude oil prices were in the range of \$25–\$30/bbl, the oil industry was concerned about a shortage of CO_2. Some estimates indicated that unless considerable quantities were made available from the electric utility industry, the amount of oil that could be recovered by CO_2 "flooding" of oil formations would be severely limited. Interest in CO_2 flooding waned, however, as oil prices dropped. Nonetheless, if oil prices increase as most observers think they will, CO_2 is expected to resume its former importance.

CO_2 produced in GCC power plants will inherently cost less than that produced in conventional power plants. To alert the electric utility industry to this potential market opportunity, EPRI contracted with Fluor Technology to develop estimates of the revenue required for CO_2 produced in GCC power plants. The results of that study (RP2221-16) are presented in detail in AP-4827 and are summarized below. But first an explanation of why CO_2 production costs would be expected to be lower in GCC plants than in conventional plants.

Figure 1 shows (in block flow) pertinent details of conditions of gas streams in nominal 500-MW plants. Two of the plants shown are a coal gasification system preparing fuel gas for its use in a combined-cycle power plant, and a conventional coal-fired system. In the plant using coal gasification, CO_2 can be produced as a mixture with hydrogen sulfide or as a separate product.

Comparing the two systems, the volume of gas that would have to be processed for CO_2 removal in the conventional plant is almost 170 times as great as that in the gasification system. Further, the partial pressure of CO_2 in the gasification system fuel gas is about 70 psia (483 kPa), whereas CO_2 pressure is only about 2 psia (14 kPa) in the conventional plant flue gas. Costs of processes that involve absorption or chemical reaction of CO_2 with a liquid (the favored processes for this purpose) tend to be strong functions of the actual volume of the gas treated and the partial pressure of CO_2. Thus, lower CO_2 production costs might be expected for the coal gasification system, even though the quantity of CO_2 would be considerably less.

The bottom of Figure 1 shows a method for increasing the quantity of CO_2 and raising its partial pressure to over 200 psia (1.38 MPa). In this case, the hot gas from the gasifier is quenched with water that is evaporated into the gas to provide steam for the shift conversion reaction, in which most of the carbon monoxide in the gas can be converted to CO_2. The cost of CO_2 in this case might be expected to be lower than that of the other gasification case. As a result of these expectations, EPRI has initiated RP2221-16.

The first step in the study was to design and cost GCC electricity-only power plants and then to design plants of the same electricity capacities that produce both electricity and CO_2. This made it possible to determine the revenue required to pay for the additional plant cost incurred to produce CO_2.

Two cases were studied: a case in which shift conversion was not used and a case using shift conversion to produce the maximum quantity of CO_2. In both cases, CO_2 product is compressed to 2000 psig (13.9 MPa) for pipeline delivery. Table 1 summarizes the results.

About 8000 std ft^3 (226 m^3) of CO_2 are required to produce one additional barrel of oil. Therefore, the CO_2 produced with no shift conversion (42 million std ft^3/d; 1.2 Mm^3/d) could yield an additional 5250 bbl/d of oil. With shift conversion employed, the 263 million std ft^3/d of CO_2 produced

ABSTRACT *Great reserves of known oil deposits remain in the ground because they cannot be extracted by conventional techniques. Injecting carbon dioxide (CO_2) into oil reservoirs is one means of recovering some of those deposits when the market price of crude oil warrants the additional production costs. When oil prices were above \$25/bbl, CO_2 was a valued commodity in the oil industry, which looked to electric utilities as a potential supplier. But recent drops in oil prices caused less interest in such recovery methods, particularly at the high cost of CO_2 extracted from conventional power plant stacks. However, CO_2 could be produced most economically by utilities if it were coproduced with electricity at coal gasification–combined-cycle (GCC) power plants. An EPRI study of two GCC plants indicates the costs might make CO_2-enhanced oil production economical even at today's oil price (about \$20/bbl).*

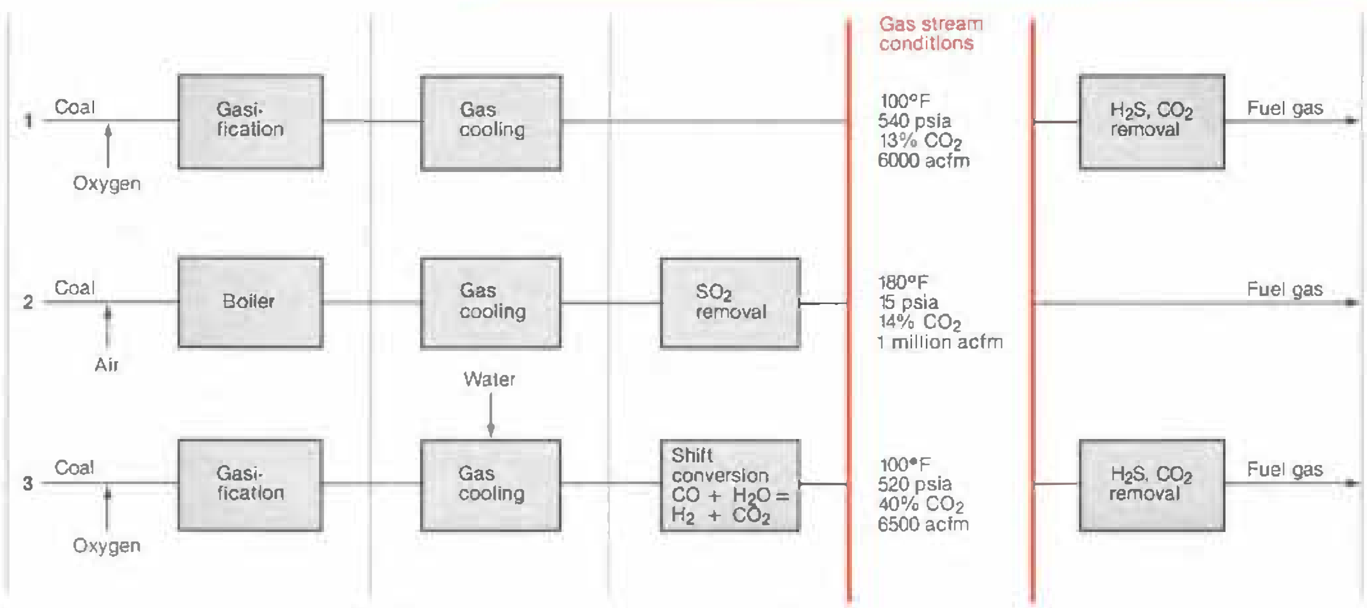


Figure 1 Gas conditions for CO_2 production. (1) Conditions are for a coal gasification–combined-cycle (GCC) plant for minimum CO_2 production; (2) a conventional coal-fired plant; and (3) a GCC plant for maximum CO_2 production. Higher pressures of CO_2 and lower actual volume of gas treated for CO_2 removal in the GCC plants led to an expectation of lower CO_2 costs.

Table 1
PLANT PRODUCTION CAPACITIES AND COSTS

	No Shift Conversion		Shift Conversion	
Plant Characteristic*	Electricity	Electricity–CO_2	Electricity	Electricity–CO_2
Net electric power (MW)	589	589	571	571
CO_2 production (million ft^3/d)	–	42	–	263
Power consumption (MW)	91	106	93	172
Coal consumption (million Btu/h)	5306	5459	5661	7003
Plant cost (million 1985 dollars)	735	780	632	870
Revenue required for CO_2 (1985 $/1000 ft^3)	–	0.85	–	0.64

*Gas volumes are for standard conditions of pressure and temperature—14.65 psia (10 kPa) and 60°F (16°C).

could yield as much as 32,900 bbl/d of oil.

The revenue requirements are considerably less than what might be required for CO_2 produced at a conventional coal-fired plant. One estimate places the latter value at about $2.50/1000 std ft^3 (28 m^3), which at 8000 std ft^3 (226 m^3) a barrel would cost $20/bbl of oil recovered. On the same basis, the costs of CO_2 estimated in this study would be $6.80/bbl of oil (no shift conversion) and $5.12/bbl of oil (with shift conversion). With oil prices (currently about $20/bbl) again on the rise, these CO_2 costs might be economically feasible even now, and oil prices will probably go higher still.

Air Quality Control

Sodium Sorbent Removal of NO_x

by John Maulbetsch and George Offen, Coal Combustion Systems Division

ABSTRACT *Control processes that remove sulfur dioxide (SO_2) by injecting dry sodium-based sorbents upstream of the baghouse at coal-fired electric power plants are effective, simple, and economically feasible. Past tests that have demonstrated the effectiveness of this technique also show the simultaneous and desirable removal of some nitrogen oxides (NO_x). A remaining issue, however, is that the NO_x removal appears linked to the conversion of some nitric oxide (NO) to nitrogen dioxide (NO_2), frequently producing a visible brownish plume. Bench-scale results of potential remedies for the brown plume problem indicate that injecting small amounts of urea into the flue gas is an effective solution. Further testing at commercial scale is expected to verify these results.*

The development of dry processes for controlling SO_2 by injecting sodium-based sorbents into the flue gases of coal-fired power plants just upstream of the particulate control device has been the subject of research at EPRI for several years. This work, which culminated in a 100-MW demonstration at the Ray D. Nixon station, Colorado Springs Dept. of Utilities, in 1986 demonstrated that the approach is effective, simple, reliable, and economical, particularly for low-sulfur coals in arid regions (EPRI CS-1744, CS-2894, FP-207, CS-4966).

Brown plume formation

One remaining issue, however, might influence the commercial application of the technology: the effect of the sodium sorbent on NO_x emissions. There is a beneficial side effect in that some NO_x is removed in conjunction with the SO_2 removal at no cost and with no deleterious effect on the primary SO_2 control function. However, the NO_x removal is accompanied by a net conversion of some of the NO to NO_2 at concentrations that may produce a visible, brownish stack plume, clearly an undesirable side effect.

The increase in NO_2 was measured at EPRI's Arapahoe Test Facility in 1986 (*EPRI Journal*, November 1986, pp. 44–45). In the field, the plume coloration problem was first noted at the Coyote station of Montana-Dakota Utilities in conjunction with the operation of a sodium carbonate (Na_2CO_3) spray dryer discharging into a baghouse. Additional pilot tests at Arapahoe and subsequent field measurements at Coyote confirmed the presence of NO_2 in concentrations ranging from 50 to 100 ppm, with most of the conversion from NO to NO_2 occurring across the baghouse and not across the spray dryer itself.

To improve understanding of the mechanisms of NO_x reduction and NO_2 production, bench- and pilot-scale tests were conducted at Arapahoe. Results of those tests suggest that NO_2 formation depends both on the absolute amount of SO_2 reacting with sodium compounds (i.e., on the quantity of SO_2 being removed) and on the quantity of NO present. Figure 1 shows these relations for a hypothetical set of conditions and a sorbent feed rate adjusted to produce 70% SO_2 removal in all cases. As the concentration of SO_2 in the inlet increases, a greater amount of SO_2 reacts with the sorbent, and the NO_2 emissions increase accordingly. Similarly, as the NO concentration increases (i.e., as the SO_2/NO ratio decreases at fixed inlet concentration of SO_2), the NO_2 emissions again rise, more rapidly when accompanied by higher inlet SO_2 concentrations than by lower SO_2 concentrations. The horizontal line at the bottom of the figure is the threshold NO_2 concentration that produces a visible plume; this threshold concentration is generally accepted to be about 30 ppm.

As part of this research effort, measurements and plume observations were conducted during the Nixon station tests to learn if NO_2 formation occurred in conjunction with the dry injection of sodium-based sorbents. These tests disclosed similar NO_2 levels and some plume coloration.

Brown plume remedies

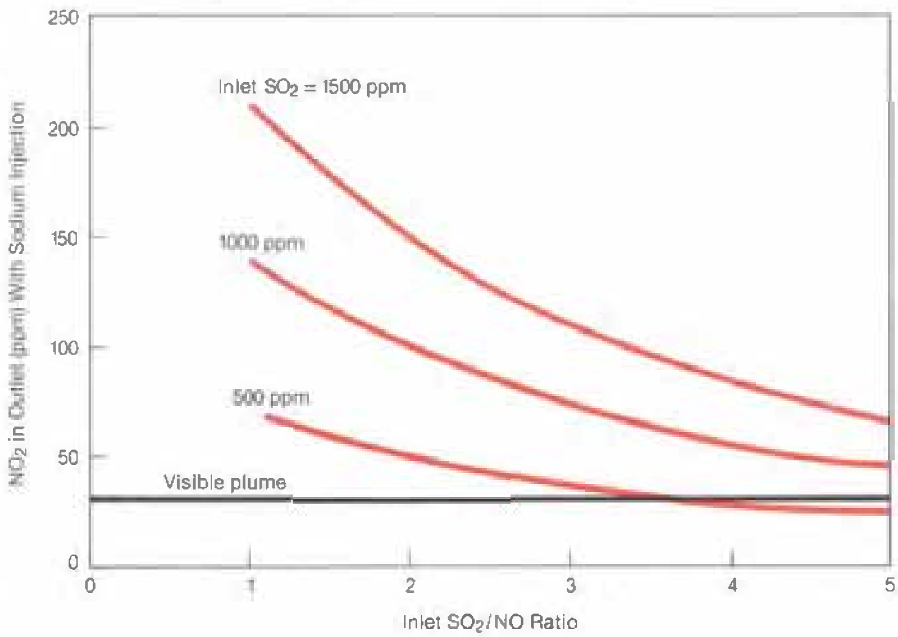
In an effort to develop and verify countermeasures for reducing NO_2 in the stack plume, a number of additives were screened. Two of these, ammonia and urea, were sufficiently effective to warrant further testing. At present, urea is preferred because it functions at lower injection concentrations. Figure 2 illustrates significant NO_2 reduction, some decrease in NO removal, and no effect on the SO_2 removed for this case.

The net result is that the use of relatively small amounts of urea eliminates the visible plume caused by NO_2, while still retaining both the design SO_2 control and significant associated NO_x reduction. Further testing is required to verify these results at commercial scale, define the effect on process economics, and ensure that no unwanted side effects result from the urea injection.

ESP tests

In general, NO and NO_x emissions recorded during ESP sodium injection tests exhibit trends similar to those observed during fabric filter testing. Increasing the sorbent feed rate to increase SO_2 removal, or doping the

Figure 1 Effect of inlet SO_2/NO ratio on NO_2 concentrations in outlet gases. The sodium injection rate is adjusted to remove 70% of the SO_2 at all inlet conditions shown. At higher concentrations of SO_2 in the inlet gases, more SO_2 reacts with the sorbent to produce higher concentrations of NO_2 in the outlet gases. Similarly, increases in NO (depicted by decreases in the SO_2/NO ratio) again cause increases in NO_2 emissions. The black line at the bottom of the graph represents the threshold NO_2 concentration for visible plumes.



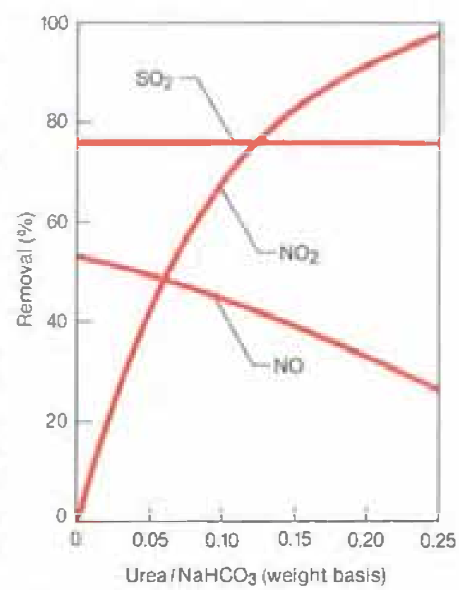


Figure 2 Effects of urea injection to reduce NO_2 emissions in sodium sorbent–treated flue gases: inlet SO_2 = 900 ppm, SO_2/NO = 1.25, NSR = 1. The SO_2 removal efficiency remains virtually constant, but the NO_2 removal efficiency increases steadily as the amount of injected urea, relative to injected $NaHCO_3$, increases. Nitric oxide removal efficiency decreases somewhat, however.

flue gas with additional SO_2 while maintaining the stoichiometry between the sorbent and SO_2, also increases the removal of NO and NO_x. The results, however, vary with flue gas temperature at fixed conditions for the other parameters. For small particles (e.g., 11 μm), NO (and also NO_x) removal is clearly better at temperatures near the low end of the range tested (335–455°F; 168–235°C). Temperature variations have much less effect when larger sorbent particles (e.g., 32 μm) are used. This trend of increasing NO_x removal with decreasing temperature is fortunate because it allows both SO_2 and NO_x to be removed with reasonable effectiveness at the relatively low temperatures typically found in the duct leading to a precipitator.

Nuclear Component Reliability

Predicting Wear in PWR Steam Generator Tubes

by David A. Steininger, Nuclear Power Division

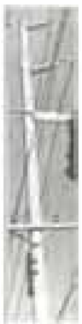
ABSTRACT *Steam generator tubes in PWRs are subject to wear that is induced by movement of the tubes within tube support structures through which the tubes pass. The clearance between the tubes and their supporting structures that allows tube movement is a design and manufacturing requisite. Predicting tube wear rates is important in preventing tube failures and the expensive plant shutdowns they can cause, as well as in complying with NRC regulations that make it mandatory to plug tubes whose wall thicknesses have been abraded by as much as 40%. In a program managed for the Steam Generator Owners Group, EPRI's Steam Generator Project Office developed a numerical method of predicting tube wear rates for tubes located in the steam generator entrance region. EPRI's wear-rate prediction method should be equally applicable to the entire heat exchanger industry.*

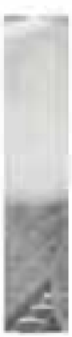
Steam generators in pressurized water reactors (PWRs) have evidenced a variety of problems, most of which are associated with corrosion-induced or mechanically induced tube and tube support plate damage. Included are vibration, fretting, high-cycle fatigue, water hammer, cracking, wastage, pitting, denting, and erosion/corrosion. In response to these problems, a utility industry research effort was funded over the last 10 years by the Steam Generator Owners Group (SGOG) and managed by EPRI's Steam Generator Project Office (SGPO). Its purpose was to identify the causes of the problems and to develop solutions for both existing and new steam generators (*EPRI Journal*, April 1978, pp. 53–56, and October 1984, pp. 20–27).

In October 1981, Ringhals Unit 3 in Sweden, a three-loop nuclear power plant with preheat-type steam generators, was shut down because of a small through-wall hole that developed in a steam generator cold leg tube; the hole was the result of wear at one of its support plates. This event motivated SGPO to develop an innovative overall method for predicting tube wear in tube bundle entrance regions. Its successful application to numerous other industrial heat exchanger designs appears quite possible. Since the Ringhals incident, several other tube vibration problems that occurred at a number of utilities made it possible to verify and calibrate the SGPO method against actual field or experimental data while the method was being developed.

In PWR steam generators, there is a clearance between the tubes, the tube support plates, and other antivibration devices through which the tubes pass. The clearance is necessary in manufacturing the steam generators, as well as for certain design reasons. If flow-induced vibratory forces are large enough, tube motion within the tube support structures can lead to unacceptable wear of either the tube or the support structure or both.

Because the steam generators are de-



signed for a 40-year life, even relatively small tube wear rates can be unacceptable. Moreover, NRC requires that only 40% of the tube wall thickness be allowed to degrade before mandatory tube plugging, which results in removal of the tube from service. Assuming a tube wall thickness of 0.050 in (1.3 mm), a wear rate of 5.0×10^{-4} in (1.3×10^{-2} mm) per operational year is allowable over the life of the unit. This allowable wear rate is not considered to be large: some operating steam generators show wear rates of approximately 30% over a period of nine years, or an average annual wall-thickness reduction rate of 1.7×10^{-3} in (4.3×10^{-2} mm).

Researchers in the nuclear steam generator industry have investigated ways of evaluating and correlating tube wear to tube motion for use in steam generator tube wear predictions. But a survey of the applicable literature, as well as tube wear problems that have surfaced over the past six years, makes it apparent that there are insufficient data and workable techniques, whether experimental or analytic, to permit the designers of PWR steam generators to predict the wear rates of multispan tubes.

Information that is available and only phenomenologically applicable appears somewhat contradictory and based on unproven assumptions. There are indications of a lack of understanding and insufficient predictive capability of the relevant flow forces that cause tube vibration in steam generators. It also appears that these same conclusions can apply to flow-induced tube vibration relevant to the heat exchanger industry as a whole.

SGPO's method for predicting tube wear takes a direct approach and minimizes arbitrary assumptions and empiricism. It consists of predicting the following.

▫ Flow-induced forces of turbulence imposed on the tubes and localized mean flow velocities between tubes

▫ Tube vibration response parameters of tube and tube support impact forces, relative sliding, and average tube and tube support contact time during tube excitation caused by flow turbulence

▫ Tube wear as a function of tube vibration response parameters

There appear to be two flow excitation mechanisms associated with steam generator tube vibration: a fluid structure instability (termed fluid elastic excitation) and flow turbulence. Well-established vortex shedding does not appear to be a flow excitation mechanism in the tight tube spacings and/or two-phase environment found in PWR steam generators. But this needs further research for those localized areas of the tube bundle that have open areas surrounded by tubes. In the past, fluid elastic excitation of steam generator tubes has been considered an extremely destructive mechanism. If operating within a tube bundle, it was thought to destroy tubes through wear or fatigue in a matter of minutes to hours. But reports of recent tests and field measurements indicate that if clearances exist between the tubes and their support structures, fluid elastic response will be amplitude-limited and result in longer-term tube damage. In any event, the prediction of fluid elastic excitation can be attempted only by using semiempirical formulas, which are, in part, a function of the mean flow velocity between tubes (termed the tube gap flow velocity).

Flow turbulence is generally considered to cause relatively low levels of tube excitation, thereby resulting in long-term wear on the order of years. Unfortunately, recent steam generator operating experience suggests that badly designed feedwater inlet regions of the steam generator can result in extremely high levels of turbulence leading to unacceptable tube wear over a period of a few thousand hours. Therefore, flow turbulence and resultant tube vibration phenomena must be investigated further.

Localized tube gap flow velocities and flow turbulence associated with a given steam generator design in the past could only be determined by very expensive prototypical testing. In many cases, probably because of the expense involved, such testing was not performed in support of the designs that are currently operating in the field.

In the first part of the SGOG method for predicting tube wear, the localized tube gap mean flow velocities and localized flow turbulence entering and within the tube bundle are calculated. The gap velocities are used in currently available semiempirical fluid elastic equations to indicate the susceptibility of the tube bundle to fluid elastic excitation.

In the process of calculating these localized tube gap flow velocities, an industry-unique computational fluid dynamic numerical procedure, termed large-eddy simulation, is used. Essentially, the numerical process calculates the time evolution of turbulence eddies that make up the flow field by solving the time-dependent form of the Navier-Stokes equations of fluid flow. The unsteady pressures applied to the steam generator tube as a result of the eddies are integrated about the tube circumference, thus providing a time history of the applied tube excitation force in both lift and drag directions. In addition, averaging the calculated and rapidly varying flow velocities over time provides the required localized tube gap mean flow velocity for fluid elastic instability evaluation. This procedure is quite different from previous techniques of flow analysis in which the steady mean flow is simply calculated directly by using the time average form of the equations. By definition, the latter approach provides no time-related information and therefore is of little use in predicting turbulence-induced tube vibration.

Large-eddy simulation is the first step in the SGOG tube wear prediction method. The turbulence associated with steam generator flows consists of eddies whose sizes vary over a large range, from those on the order of the flow field geometry (e.g., diameter of a pipe) down to sizes that immediately dissipate into heat by viscous action. Specifically, for Reynolds numbers of about 10^4, say, the range of eddy sizes involved covers some three orders of magnitude. Operating Reynolds numbers in steam generators are on the order of 10^6. Present-day supercomputers and those envisioned for the foreseeable future simply cannot handle such immense problems of calculating this range of eddy size, it is not certain that they will ever be able to do so. But it appears that turbulence phenomena exhibit a characteristic that simplifies the calculation effort.

As an eddy becomes smaller its associated intrinsic energy decreases. There is a universal character associated with the smaller turbulence eddies. They have no effect on the large-scale properties of the flow and simply allow flow energy to be dissipated as it cascades down from the breakup of large eddies; the larger eddies are dependent on the geometry in which the flow develops. Therefore, it is suggested that one need accurately calculate only the large-scale turbulence and model the small-scale turbulence within the numerical simulation through some type of correlation that depicts energy dissipation within the flow. It is hoped that because of the universal nature of the small-scale turbulence, this correlation will be independent of the subject flow geometry.

The same correlation can be applied to any flow geometry problem without alteration. In essence, this is the large-eddy simulation technique. Its application to engineering-type problems is now being considered because of the relatively recent significant increases in computer power. But what also makes large-eddy simulation particularly attractive for evaluating flow-induced vibration in steam generators is the relationship between the sizes of the vibrating tube and of the effective eddy that causes a substantial amount of the tube vibratory response. Efficient energy coupling between flow turbulence and the tube occurs when a characteristic eddy size of the turbulent flow field is on the order of a tube diameter and when its associated characteristic frequency equals the natural frequency of the tube.

Steam generator tubes exhibit natural frequencies in the range of 10–40 Hz. In addition, some researchers believe that the characteristic (i.e., effective) eddy size, or eddy correlation length, for maximum energy transfer to the tube is about four times the tube diameter (e.g., about 3.0 in; 7.6 cm). Numerical finite difference techniques using mesh sizes of about 1 in (2.5 cm) for the subject flow geometry with time differencing of about 5 ms are now computationally feasible. With supercomputers (Cray XM-P series or Cray 2) this becomes an extremely practical design tool. It is noted, however, that the successful development and application of large-eddy simulation, as part of SGPO's tube wear predictive methods, were achieved on a Univac mainframe computer.

The alternating forces applied to the tube as calculated by the large-eddy simulation technique are used in a simulation of the tube's movement within its support structures. This is the second step of the SGOG tube wear prediction method. The simulation consists of one tube in its multispan configuration. The simulation can be experimental or numerical. The simulation determines those aspects of the interaction between the tube and the tube support that are involved in tube wear.

The important interaction characteristics are tube support structure reaction forces, the relative sliding distance between tube and support, and the average time of contact between the tube and its support. The average time of contact is an indication of the proportion of sliding-type action to direct impact between the tube and support structure. Depending on this proportion, the physics of wear can be considerably different. The reaction force and sliding distance are important parameters in empirical sliding and fretting wear-type correlations.

In its present state of development the method depends on both experimental and finite-element simulation of a multispan tube. The experimental simulation not only provides the interaction characteristics but also calibrates the numerical simulation. There are a few parameters in the numerical simulation not now quantifiable for the geometry of any given tube and tube support. Two such parameters are fluid damping and inertial resistance in the fluid-filled crevice created by the tube and its support structure. The numerical simulation is then used for future investigations and for sensitivity studies long after the test fixture has been dismantled.

Tube dynamic simulation can be carried out in test apparatus that provide for measuring the interactions between tubes and their supporting structures. The numerical simulation of tube dynamics is performed by using EPRI's nonlinear, finite-element code ABAQUS-EPGEN. The code required modification by the code developer in order to handle the specific problem of tube impacting and sliding against the various support structures. Nonlinear damping, stiffness, and friction elements were added as the interface between the tube and its support structures. They are constructed in a manner that allows exact representation of clearances between the tube and its supporting structure. Damping elements were added along the length of the tube to simulate viscous damping of the tube in the surrounding environment during tube movement. Also, options to use numerical approximations of substructuring and modal analysis have been added as possible means of reducing computation costs of the highly complicated nonlinear, time-dependent problem. To date, these methods have not been satisfactorily verified, and they need extensive investigation.

Results obtained with the ABAQUS-EPGEN code have been compared with limited multispan tube tests; the agreement between code and test results is excellent. The code predicts the characteristics of the interaction between tube and tube support (which are so important in determining tube wear) as accurately as do the multispan tube tests but at a much reduced cost and with increased versatility. Figure 1 shows typical calculated tube trajectories within a series of three Combustion Engineering steam generator support plates placed along a tube. These trajectories and certain tube–tube support plate interaction parameters involved in tube wear have compared favorably with test measurements.

It is hoped that after additional experimentation to quantify tube and tube support crevice damping and added mass, and after code verifications are completed, the

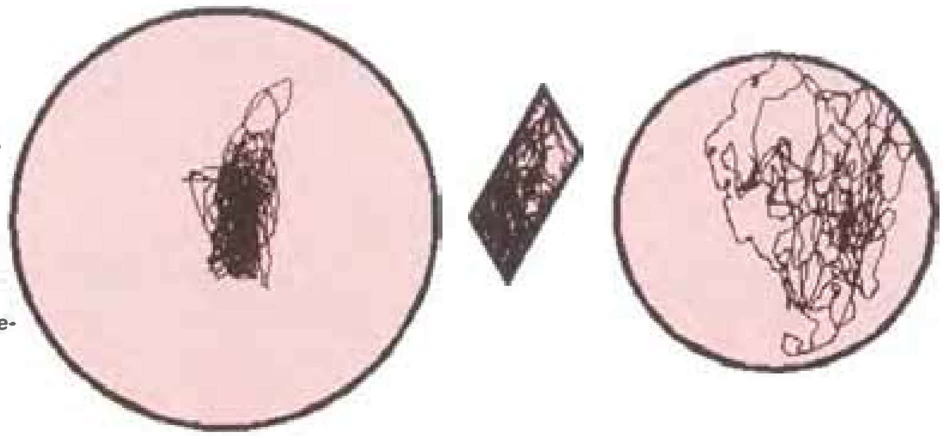


Figure 1 Numerically calculated orbital tube motion of a single tube within three different types of Combustion Engineering tube supports located along the tube. Initially, the tube was centered within the supports with a point source of 0.0254 lb^2/Hz random force excitation applied to the tube. When compared with test measurements, the agreement is considered excellent.

ABAQUS–EPGEN code will supplant testing as a means of obtaining tube and tube support interaction characteristics.

After the important wear parameters (support structure reaction forces, relative sliding distance between tube and support, and average time of contact between tube and support) have been obtained through test or numerical simulation, empirical correlations relate volumetric wear rates to these parameters. These correlations were developed from high-temperature autoclave tests in which a single tube can be vibrated within a highly instrumented support structure under controlled tube excitation conditions, and the tube wear was measured. The correlations were developed to cover a range of the independent parameters for various tube support materials. If a tube wall thickness reduction rate or wall penetration rate is to be calculated, a wear scar geometry is assumed and used with the volumetric wear rate.

It is believed that this is the first nuclear industry application of the advanced computational fluid dynamic technique known as large-eddy simulation, and it may be the first use of the technique in the heat exchanger industry as a whole. EPRI's method for predicting steam generator tube wear need not be limited to nuclear power plants. It is equally applicable to heat exchangers in general, in which shell-side flow induces tube vibration and wear. Further development and verification of the method is continuing in EPRI's Nuclear Power Division.

New Contracts

Project	Funding / Duration	Contractor / EPRI Project Manager
Advanced Power Systems		
Prototype Photovoltaic Module Construction and Testing (RP1415-16)	$248,400 7 months	Cummings Engineering Inc / *F. Dostalek*
High-Concentration Photovoltaic Module Testing Support (RP1415-19)	$45,700 5 months	Scientific Analysis / *F. Dostalek*
High-Concentration Photovoltaic Module Testing Support (RP1415-21)	$32,900 5 months	EOS Electric Power Inc / *F. Dostalek*
KILnGAS Data Analysis: Mass and Energy Balance (RP1654-37)	$58,900 6 months	Radian Corp / *N. Hertz*
Feasibility Study: Growth of Simple Crystal Superalloys by the Direct Czochralski Method (RP2382-6)	$67,700 1 year	Unisil Corp. / *R. Frischmuth, R. Jaffee*
CAES Plant Availability and Reliability Model (RP2488-15)	$96,000 17 months	Arinc Research Corp / *R. Pollak*
IGCC Site-Specific Study (RP2773-10)	$120,000 1 year	Fluor Technology Inc / *M. Gluckman*
Instrumentation Requirements for Gas Turbine Durability Monitoring (RP2774-3)	$51,300 11 months	Dow Engineering Co / *C. Dohner*
Coal Combustion Systems		
Scoping Study: Manufactured-Gas Plant Sites (RP1260-60)	$51,900 3 months	Mittelhauser Corp / *M. McLearn*
Condenser On-Line Leak Detection System Development (RP1689-19)	$99,900 1 year	Stone & Webster Engineering Corp / *J. Tsou*
Steam Turbine Blade Life Improvement (RP1856-7)	$2,724,700 2 years	Stress Technology Inc / *T. McCloskey*
BLADE Code Verification and Evaluation (RP1856-8)	$238,000 18 months	Lehigh University / *T. McCloskey*
Feed Pump Hydraulic Performance and Design Improvement (RP1884-18)	$1,827,000 42 months	Pradco / *S. Pace*
Preventive Measures: Economizer Inlet Header Cracking in Fossil Fuel Boilers (RP1890-6)	$152,000 9 months	Ontario Hydro / *D. Broske*
Site 3 Field Testing: Behavioral Barriers for Cooling Water Intake Systems (RP2214-8)	$458,800 1 year	Lawler, Matusky & Skelly / *W. Micheletti*
Electrical Systems		
Substation Evaluation: Diagnostic Logic System (RP2115-1)	$74,200 9 months	Andtek, Inc. / *L. Mankoff*
Scoping Study: Integrated Utility Communication Systems (RP2592-5)	$144,600 5 months	ECC, Inc. / *W. Kubicki*
Aging of Extruded Dielectric Power Cables (RP2713-1)	$1,375,500 80 months	Cable Technology Laboratories, Inc / *B. Bernstein*
Active Transformer Noise Cancellation System (RP2744-1)	$374,900 20 months	Angevine Acoustical Consultants, Inc. / *S. Wright*
Methods for Substation Voltage Upgrading (RP2794-1)	$195,300 1 year	General Electric Co / *J. Porter*
Assessment: High-Temperature Superconductor Potential in Utility Applications (RP7898-1)	$100,000 5 months	Department of Energy / *D. Sharma*

Project	Funding / Duration	Contractor / EPRI Project Manager
Energy Management & Utilization Division		
Conversion of Bedford CF Van to Nickel-Iron Battery Propulsion (RP1136-32)	$112,500 4 months	Eagle-Picher Industries Inc / *G. Purcell*
Development: Demand-Side Screening Model (RP1485-9)	$247,000 13 months	DFI/Electric Power Software / *P. Hanser*
Value-Based Planning (RP1485-10)	$40,000 5 months	Putnam, Hayes & Bartlett, Inc / *P. Hanser*
District Heating and Cogeneration Potential (RP1538-3)	$105,500 2 years	Studsvik Energiteknik AB / *C. Gellings*
Applications of Electronic Adjustable-Speed Drives (RP1966-24)	$60,200 5 months	Regents of the University of California / *M. Samotyj*
End-Use Forecasting Model: Agricultural Sector (RP2340-2)	$58,900 7 months	Quantum Consulting, Inc / *R. Squitieri*
Demand Defrost of Commercial Warehouse Refrigeration Systems (RP2569-3)	$61,400 7 months	California State University Fresno Foundation / *M. Blatt*
Customer Preference and Behavior (RP2671-2)	$233,400 19 months	Utility-Customer Interface Inc / *L. Lewis*
Heat and Power System Design: Industrial Processes (RP2783-9)	$305,100 13 months	Linnhoff-March, Inc. / *A. Karp*
Industrial Heat Pump Manual (RP2783-11)	$107,600 8 months	Linnhoff-March, Inc / *A. Karp*
Nuclear Power		
Effects of Thermal Treatments on the Corrosion Resistance of Alloy 690 Tubing (S408-2)	$90,300 17 months	Inco Alloys International Inc / *C. Shoemaker*
Fluid Film Effects in Various Steam Generator Tube Support Geometries (S410-4)	$83,100 1 year	Combustion Engineering, Inc. / *D. Steininger*
Applications of Electromagnetic Transducers to the Inspection of BWR Mark-I Containment Vessels (RP1570-21)	$75,300 6 months	Innovative Sciences Inc / *M. Avioli*
Third Riso Fission Gas Project (RP1702-11)	$479,600 4 years	Riso National Laboratory / *R. Yang*
Requirements for In-service Inspection of Nuclear Plant Components (RP2057-7)	$99,000 5 months	Science Applications International Corp / *M. Behravesh*
Technical Specification Improvements to Emergency Core Cooling and Containment Heat Removal Systems (RP2142-3)	$127,500 9 months	General Electric Co / *J. Gaertner*
Planning and Evaluation		
Education Program: Equivalent Load Duration Curves (RP1808-7)	$50,000 7 months	Ohio University / *J. Delson*
Utility Planning Model Support (RP1819-60)	$119,900 15 months	Arthur Andersen & Co / *S. Chapel*
Capital Budgeting in Utilities (RP1920-5)	$55,100 7 months	Incentives Research Inc / *S. Chapel*
Priority Service Methods (RP2801-2)	$1,251,000 17 months	Applied Decision Analysis / *H. Chao*

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

Investigation of Sulfur Removal From Low-Pressure Gas
AP-5102 Final Report (RP2221-19); $25
Contractor: Mittelhauser Corp.
EPRI Project Manager: R. Frischmuth

Meager Creek Geothermal Project
AP-5118 Final Report (RP1196-4, -90); $25.00
Contractors: British Columbia Hydro and Power Authority; Barber-Nichols Engineering Co.
EPRI Project Manager: E. Hughes

Compressed-Air Energy Storage: An Analysis of Fuel Flexibility and Plant Components
AP-5122 Final Report (RP1791-8); $47.50
Contractor: BBC Brown Boveri, Inc.
EPRI Project Manager: R. Schainker

Hydrogen Enrichment of Synthesis Gas for Once-Through Methanol Production
AP-5123 Final Report (RP2654-1); $32.50
Contractor: Stearns Catalytic Corp.
EPRI Project Manager: B. Louks

Upstream Hydrogen Sulfide Removal Test at the Cerro Prieto Geothermal Field
AP-5124 Final Report (RP1197-6); $32.50
Contractor: Instituto de Investigaciones Electricas
EPRI Project Manager: E. Hughes

Simulator-Analyzer for Binary-Cycle Geothermal Power Plants
AP-5134 Final Report (RP2195-7), Vol. 1; $25
Contractor: ESSCOR
EPRI Project Manager: J. Bigger

EPRI Roles in Fuel Cell Commercialization
AP-5137 Final Report (RP1677-15); $25
Contractor: Decision Focus Inc.
EPRI Project Managers: J. Birk, E. Gillis

Characterization of Coal Pyrolysis Liquids
AP-5165 Final Report (RP2505-3); $25
Contractor: University of Utah
EPRI Project Manager: L. Atherton

Hydrogenated Amorphous Silicon Films Produced by Chemical Vapor Deposition
AP-5166 Final Report (RP1193-2); $25
Contractor: Poly Solar Inc.
EPRI Project Managers: J. Crowley, T. Peterson

The New Promod III Combined-Cycle Module
AP-5204 Final Report (RP2699-7); $32.50
Contractor: Energy Management Associates, Inc.
EPRI Project Manager: A. Lewis

Catalyst Performance and Life in Liquid-Phase Methanol
AP-5205 Final Report (RP2563-2); $25
Contractor: Air Products and Chemicals, Inc.
EPRI Project Manager: C. Kulik

Repowering Reheat Units With Gas Turbines
AP-5216 Final Report (RP2565-5); $25
Contractor: Virginia Power
EPRI Project Manager: H. Schreiber

Coal Pretreatment With Carbon Dioxide and Water: Effects on North Dakota Lignite and Utah Coal
AP-5222 Final Report (RP1654-25); $25
Contractor: Brookhaven National Laboratory
EPRI Project Manager: N. Hertz

COAL COMBUSTION SYSTEMS

Laser Doppler Vibration Testing
CS-5031 Final Report (RP1855-2); $40
Contractor: General Electric Co.
EPRI Project Manager: J. Scheibel

Acoustic Boiler Tube Leak Detection: Utility Experience
CS-5136 Final Report (RP1863-2); $285
Contractor: Battelle, Columbus Division
EPRI Project Manager: J. Scheibel

Wear Measurement by Surface Layer Activation
CS-5163 Interim Report (RP1957-3); $535
Contractor: Spire Corp.
EPRI Project Manager: J. Scheibel

Guideline Manual on Instrumentation and Control for Fossil [Fuel] Plant Cycle Chemistry
CS-5164 Final Report (RP2712-2); $1,050
Contractor: Sheppard T. Powell Associates
EPRI Project Manager: B. Dooley

Proceedings: Tenth Symposium on Flue Gas Desulfurization
CS-5167 Proceedings (RP982-40); Vol. 1, $55; Vol. 2, $55
Contractor: Radian Corp.
EPRI Project Manager: R. Moser

Intake Operation for Deep Cooling Reservoirs
CS-5170 Final Report (RP2385-1); $25
Contractor: Massachusetts Institute of Technology
EPRI Project Manager: J. Bartz

Analysis of Evaporation Data From Heated Ponds
CS-5171 Final Report (RP2385-1); $32.50
Contractor: Massachusetts Institute of Technology
EPRI Project Manager: J. Bartz

Field Evaluation of Arsenic and Selenium Removal by Iron Coprecipitation
CS-5187 Final Report (RP910-3); $40
Contractor: Brown and Caldwell
EPRI Project Manager: W. Chow

ELECTRICAL SYSTEMS

Improvement in Accuracy of Prediction of Electrical Machine Constants and Generator Models for Subsynchronous Resonance Conditions
EL-3359 Final Report (RP1288-1, RP1513-1); Vol. 3, $32.50
Contractor: General Electric Co.
EPRI Project Manager: D. Sharma

Optimization of Induction Motor Efficiency
EL-4152 Final Report (RP1944-1), Vol. 2; $62.50
Contractor: University of Colorado
EPRI Project Manager: J. White

A Remote Tester for Surge Arresters
EL-4953 Final Report (RP2004-1); $25
Contractor: McGraw Edison Power Systems
EPRI Project Manager: H. Songster

Characterization of By-Products of Sulfur Hexafluoride and Polymeric Construction Materials
EL-5089 Final Report (RP7897-4); $32.50
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: B. Bernstein

Guidelines for Evaluation of Generator Retaining Rings
EL/EM5117-SR Special Report; $25
EPRI Project Managers: J. Stein, R. Viswanathan

Light-Fired Thyristor Development
EL-5125 Final Report (RP567-1); $25
Contractor: Westinghouse Electric Corp.
EPRI Project Manager: J. Marks

Proceedings: Workshop on Substitute Insulation for Polychlorinated Biphenyls
EL-5143-SR Proceedings; $32.50
EPRI Project Manager: G. Addis

Measurement and Analysis of Switching Transients in Gas-Insulated Transmission Lines
EL-5145 Final Report (RP7902-1); $32.50
Contractor: Mississippi State University
EPRI Project Manager: T. Rodenbaugh

Composite System Reliability Evaluation Methods
EL-5178 Final Report (RP2473-10); $32.50
Contractor: Centro de Pesquisas de Energia Electrica
EPRI Project Manager: N. Balu

Composite Generation-Transmission Expansion Planning
EL-5179 Final Report (RP2473-9); $32.50
Contractor: Centro de Pesquisas de Energia Electrica
EPRI Project Manager: N. Balu

ENERGY MANAGEMENT AND UTILIZATION

Structural Composite Cores for Overhead Power Transmission Conductors
EM-5110 Final Report (RP2426-9); $25
Contractor: Battelle, Columbus Division
EPRI Project Managers: R. Viswanathan, R. Kennon

FORECAST MASTER Program Case Studies
EM-5114 Final Report (RP2279-2); $40
Contractor: Quantitative Economic Research, Inc.
EPRI Project Manager: R. Squitieri

Guidelines for Evaluation of Generator Retaining Rings
EL/EM-5117-SR Special Report; $25
EPRI Project Managers: J. Stein, R. Viswanathan

Energy-Use Patterns and Indicators
EM-5126 Final Report (RP1940-16); Vol. 1, $40; Vol. 2, $40
Contractor: Synergic Resources Corp.
EPRI Project Manager: S. Hu

Forecasting in an Era of Marketing, Conservation, and Competition
EM-5142 Proceedings (RP1955-4); $40
Contractor: Battelle, Columbus Division
EPRI Project Manager: S. Braithwait

Nondestructive Evaluation of Grain Boundary Segregation
EM-5154 Final Report (RP2426-7); $32.50
Contractor: Daedalus Associates, Inc.
EPRI Project Manager: R. Viswanathan

Proceedings: Meeting Customer Needs With Heat Pumps
EM-5168 Proceedings (RP2597-9); $62.50
Contractor: Policy Research Associates, Inc.
EPRI Project Manager: M. Blatt

Customer Preference and Behavior: Residential Modeling Framework
EM-5217 Final Report (RP2671-1); $47.50
Contractor: Booz, Allen & Hamilton Inc.
EPRI Project Manager: L. Lewis

Competition: Pressures for Change
EM-5226 Final Report (RP2381-6); $25
Contractor: Price Waterhouse
EPRI Project Manager: C. Gellings

ENVIRONMENT

Field Evaluation of Instruments for the Measurement of Unsaturated Hydraulic Properties of Fly Ash
EA-5011 Interim Report (RP2485-7); $32.50
Contractor: RMT, Inc.
EPRI Project Manager: D. McIntosh

Chemical Form and Leachability of Inorganic Trace Elements in Coal Ash
EA-5115 Final Report (RP1371-1); $40
Contractor: University of Southern California
EPRI Project Managers: R. Perhac, J. Guertin

Matrix Isolation Spectroscopy and the Stability of Polycyclic Aromatics in Coal Ash
EA-5148 Final Report (RP1307-1); $40
Contractor: University of Tennessee
EPRI Project Managers: J. Guertin, R. Perhac, P. Jones

Measurement of Bioavailable Mercury Species in Fresh Water and Sediments
EA-5197 Final Report (RP2020-3); $32.50
Contractor: Battelle, Pacific Northwest Laboratories
EPRI Project Managers: J. Huckabee, D. Porcella

Compensatory Mechanisms in Fish Populations: Literature Reviews
EA-5200 Final Report (RP1633-6); Vol. 1, $40; Vol. 2, $32.50; Vol. 3, $40
Contractors: University of Rhode Island; University of Michigan; Systech Engineering, Inc.
EPRI Project Manager: J. Mattice

Mechanisms of Compensatory Response of Fish Populations: Workshop Proceedings
EA-5202 Proceedings; $47.50
Contractors: R. G. Otto & Associates; Science Applications International Corporation
EPRI Project Manager: J. Mattice

NUCLEAR POWER

Influence of Fuel-Cycle Duration on Nuclear Unit Performance
NP-5042 Topical Report (RP2490-3); $32.50
Contractor: The S. M. Stoller Corp.
EPRI Project Manager: F. Gelhaus

EPRI Workshop on Piping Integrity, 1986
NP-5051-SR Special Report; $25
EPRI Project Managers: B. Chexal, D. Norris, H. Tang

Proceedings of the Committee on the Safety of Nuclear Installations Specialists' Meeting on Core Debris-Concrete Interactions
NP-5054-SR Special Report; $55
EPRI Project Manager: R. Ritzman

PWR Secondary Water Chemistry Guidelines
NP-5056-SR Special Report; $32.50
EPRI Project Manager: C. Welty

Analysis of Cracked Pipe Weldments
NP-5057 Final Report (RP2457-5); $32.50
Contractor: Combustion Engineering, Inc.
EPRI Project Manager: D. Norris

Testing of the ENDF/B-V Nuclear Data Library in Thermal Benchmark Experiments
NP-5058 Final Report (RP975-1, RP2352-2); $25
Contractor: Brookhaven National Laboratory
EPRI Project Manager: O. Ozer

Corrosion-Assisted Cracking of Stainless and Low-Alloy Steels in LWR Environments
NP-5064M Final Report (RP2006-6); $32.50
NP-5064S Final Report (RP2006-6); $200
Contractor: General Electric Co.
EPRI Project Manager: J. Gilman

Specially Prepared Alloy 600 Tubing
NP-5072 Final Report (RPS303-17); $40
Contractor: Babcock & Wilcox Co.
EPRI Project Manager: A. McIlree

Caustic Concentration in Tube Support Plate Crevices of Steam Generators
NP-5073 Topical Report (RPS311-4); $40
Contractor: Commissariat à l'Energie Atomique
EPRI Project Manager: C. Shoemaker

Evaluation of Changing PWR Polisher Operation From Regenerated to Throwaway Resins
NP-5074 Final Report (RPS306-13); $25
Contractor: NWT Corp.
EPRI Project Managers: S. Hobart, C. Welty

Updated Scaling Factors in Low-Level Radwaste
NP-5077 Final Report (RP1557-6); $32.50
Contractors: Impell Corp.; Advanced Process Technology
EPRI Project Manager: P. Robinson

Hydrogen Water Chemistry for BWRs: Materials Behavior
NP-5080 Interim Report (RP1930-1); $25
Contractor: General Electric Co.
EPRI Project Managers: J. Nelson, R. Jones

An Evaluation of the Use of Signal Validation Techniques as a Defense Against Common-Cause Failures
NP-5081 Final Report (RP2448-4); $25
Contractor: Los Alamos Technical Associates, Inc.
EPRI Project Manager: B. Sun

Utility Guide to Advanced Ultrasonic Systems for Preservice and In-Service Inspections
NP-5086 Topical Report (RP2057-6); $32.50
Contractor: VinTek, Inc.
EPRI Project Manager: M. Avioli

Snubber Elimination Using Energy Absorbers
NP-5096 Final Report (RP1586-2); $25
Contractor: Bechtel Western Power Corp.
EPRI Project Manager: H. Tang

New Computer Software

The Electric Power Software Center (EPSC) provides a single distribution center for computer programs developed by EPRI. The programs are distributed under license to users. No royalties are charged to nonutility public service organizations in the United States, including government agencies, universities, and other tax-exempt organizations. Industrial organizations, including nonmember electric utilities, are required to pay royalties. EPRI member utilities, in paying their membership fees, prepay all royalties. Basic support in installing the codes is available at no charge from EPSC; however, a consulting fee may be charged for extensive support.

For more information about EPSC and licensing arrangements, EPRI member utilities, government agencies, universities, and other tax-exempt organizations should contact the Electric Power Software Center, UCCEL Corp., 1930 Hi Line Drive, Dallas, Texas 75207; (214) 655-8883. Industrial organizations, including nonmember utilities, should contact EPRI's Manager of Licensing, P.O. Box 10412, Palo Alto, California 94303; (415) 855-2866.

CHEMTRACE: Database of Tradename Hazard Profile
Version 1.0 (IBM PC); EA-5212
Contractor: Dynamac Corp.
EPRI Project Manager: W. Weyzen

COOLADD: Generic Cooling Water Additives Database
Version 1.0 (IBM PC); CS-5133
Contractor: Utility Data Institute
EPRI Project Manager: W. Micheletti

COOLAID: Thermal Energy Storage/Demand-side Planning/Load and Market Research
Version 1.0 (IBM PC)
Contractor: Regional Economic Research, Inc.
EPRI Project Manager: S. Braithwait

DCMP: Methodology for the Integration of HVDC Links in Large Ac Systems
Version 1.0 (IBM XA); EL-4365
Contractor: Manitoba HVDC Research Center
EPRI Project Manager: N. Balu

LOADSYN: Load Modeling for Power Flow and Transient Stability Computer Studies
Version B-000 (IBM); EL-5003
Contractor: General Electric Co.
EPRI Project Manager: J. Mitsche

UFIM: Utility Fuel Inventory Model
Version 2.1 (IBM PC); EA-4766
Contractor: Applied Decision Analysis, Inc.
EPRI Project Manager: S. Chapel

Calendar

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

OCTOBER

26–29
7th Annual Coal Gasification Contractors' Conference
Palo Alto, California
Contact: Neville Holt (415) 855-2503

26–30
Rotor Bearing Analysis Technique
Charlotte, North Carolina
Contact: Stanley Pace (415) 855-2826

27–28
Coal Markets and Utilities' Compliance Decisions
St. Louis, Missouri
Contact: Jeremy Platt (415) 855-2628

28–30
Fish Protection at Steam and Hydro Power Plants
San Francisco, California
Contact: Wayne Micheletti (415) 855-2469

NOVEMBER

5–6
6th Reactor Physics Software Users Group Meeting
Palo Alto, California
Contact: Walter Eich (415) 855-2090

10–12
Conference: Boiler Tube Failures in Fossil Fuel Plants
Atlanta, Georgia
Contact: Barry Dooley (415) 855-2458 or David Broske (415) 855-8968

17–18
8th Annual EPRI NDE Information Meeting
Palo Alto, California
Contact: Soung-Nan Liu (415) 855-2480

17–18
Regional Seminar: FGD Operations
Indianapolis, Indiana
Contact: Rob Moser (415) 855-2277

29–December 2
Fly Ash and Coal Conversion By-products
Boston, Massachusetts
Contact: Ishwar Murarka (415) 855-2150

DECEMBER

1–2
Workshop: Weld Repair of High-Pressure and Intermediate-Pressure Turbine Rotors for Life Extension
Palo Alto, California
Contact: Jeff Byron (415) 855-8967

1–3
Fossil Fuel Plant Retrofits for Improved Availability and Heat Rate
San Diego, California
Contact: George Touchton (415) 855-8935

2–3
Acid Rain: A View From the States
Washington, D.C.
Contact: Ralph Perhac (415) 855-2572

2–3
Regional Seminar: FGD Operations
Dallas, Texas
Contact: Rob Moser (415) 855-2277

7–10
Seminar: Probability Methods for Generation Costing
Athens, Ohio
Contact: Jerry Delson (415) 855-2619

8–10
Seminar: Availability and Reliability of Large Turbines and Hydraulic Generators
Scottsdale, Arizona
Contact: Jim Edmonds (415) 855-2291

10–11
BENCHMARK Demonstration and Users Group Meeting
Athens, Ohio
Contact: Jerry Delson (415) 855-2619

MARCH

16–18
PWR Primary Chemistry and Radiation Field Control
Berkeley, California
Contact: Chris Wood (415) 855-2379

MAY

3–5
1988 Seminar on AFBC Technology for Utility Applications
Palo Alto, California
Contact: Stratos Tavoulareas (415) 855-2424

Authors and Articles


Sagan


Black


Sussman


Rafferty


Shula


Ng


Jeffress

EMF: The Debate on Health Effects (page 4) was written by Michael Shepard, *Journal* feature writer, with background information from members of EPRI's Environment Division.

Leonard Sagan, a physician and senior scientific adviser, heads the Radiation Studies Program. Before coming to EPRI in 1978 he was with the Palo Alto Medical Clinic for 10 years as associate director of environmental medicine. He once directed medical research for the Atomic Bomb Casualty Commission in Japan and was later an AEC researcher in nuclear medicine. Sagan earned an MD at the University of Chicago, and an MPH at the Harvard School of Public Health.

Robert Black, with EPRI since 1979, manages research in the epidemiology of electromagnetic field effects. He came to EPRI from the University of Texas, School of Public Health, where he earned an MPH. He had earlier worked as the field program manager for Amigos de las Américas, an international public health program.

Stanley Sussman is a physicist who manages research projects on exposure assessment. He joined EPRI early this year after five years as a vice president for 3H Industries, where he had successive responsibilities in electronic instrument development and marketing. Sussman worked for EPRI between 1978 and 1981, involved in economic modeling and planning research. Still earlier he coordinated an energy modeling effort at Lawrence Livermore Laboratory. Sussman has an MS from Stevens Institute of Technology, and a PhD in physics from City College of New York.

Charles Rafferty, a biophysicist and project manager for basic scientific study of field effects, joined EPRI this year after five years as a research chemist with the Walter Reed Army Institute of Research. He has also worked for the National Institutes of Health, the Office of Naval Research, and the National Eye Institute. Rafferty has a PhD from Ohio State University. ■

Stewart Udall: Conservationist by Heritage (page 16) updates the career of a former secretary of the interior who now serves on EPRI's Advisory Council. This profile was written by feature editor Ralph Whitaker, after an interview with Udall. ■

Transformers With Lower Losses (page 22) was written by John Douglas, science writer, with technical assistance from two members of EPRI's Electrical Systems Division.

Bill Shula, who has managed the Distribution Program for 10 years, was previously with Texas Electric Service for 27 years. He graduated from Texas A&M in electrical engineering.

Harry Ng, a project manager, came to EPRI in 1983 after 12 years in distribution engineering with Tucson Electric Power. Ng has a BS in electrical engineering from the University of Arizona. ■

Supporting Business With Infrared Processing (page 28) was written by Jon Cohen, science writer, aided by **Robert Jeffress** of EPRI's Energy Management and Utilization Division. Jeffress, a project manager for research in metals production and fabrication, came to EPRI in 1986 after 13 years with the American Iron and Steel Institute, where he was director of technology. He previously worked in metallurgy and quality control with Armco Steel Corp. Jeffress graduated in metallurgical engineering from Purdue University. ■

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