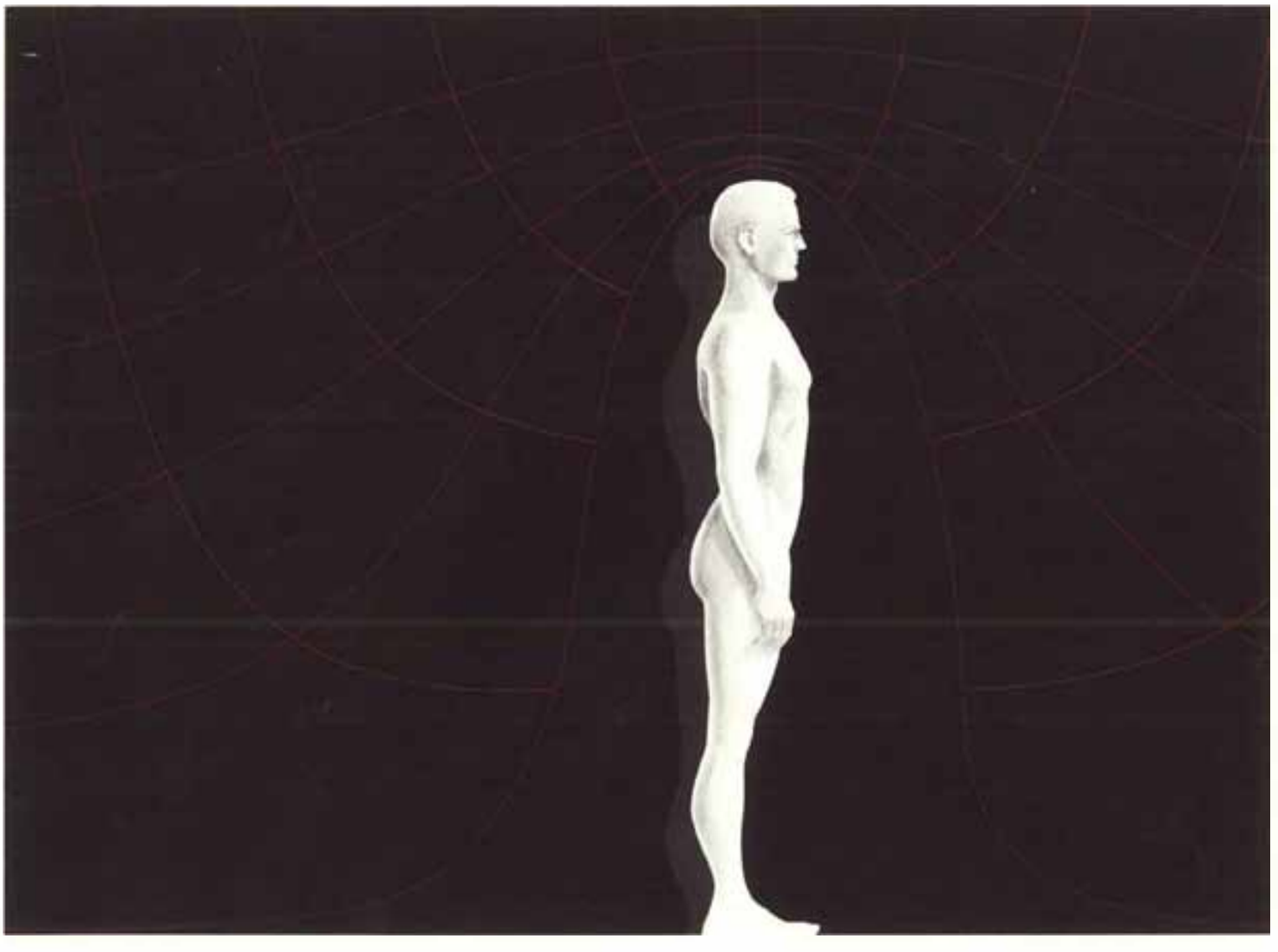
Concern Overhead

ELECTRIC POWER RESEARCH INSTITUTE

EPRI JOURNAL

NUMBER
FIVE

JUNE/JULY
1977



EPRI JOURNAL is published by the
Electric Power Research Institute.

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

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EPRI JOURNAL INDEX

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Cover: Human figure standing in electromagnetic field generated by high-voltage line causes distortion in invisible field, represented by a simplified plot. Figure causes flow lines to crowd at its head, increasing field intensity there. Whether harmful biological effects result from such exposure is under investigation.

EPRI JOURNAL

Volume 2, Number 5 June/July 1977

Controversy Over High-Voltage Effects

The present controversy over possible health and environmental effects from high-voltage transmission lines points up how public concern can mount and how science and industry can respond positively to environmental problems. With a large dose of truth and a dash of cynicism, it has been said that in today's world, environmental issues tend to be emotional, environmental decisions are largely political, and environmental solutions are scientific and technical.

EPRI's environmental research program is aimed at developing an improved, reliable, and credible data base so that with time, the issues will become less emotional, the decisions less political, and the solutions more satisfactory and cost-effective, better balanced between engineering control and biological knowledge, and more clearly understood by the public.

Whenever an environmental concern surfaces in connection with a technological option or process, the scientific and technical community makes an immediate assessment based on existing knowledge and experience. This is to ensure that any action needed to avoid imminent harm to the public welfare is taken promptly. Research on the possible effects of electric fields from high-voltage transmission lines began in the 1960s. Public awareness increased in the 1970s, triggered primarily by reports from the Soviet Union describing medical complaints from switchyard workers exposed to high-voltage gradients for long periods.

Drawing on experience and observation, the immediate assessment shows that all living organisms have always been exposed to natural electric and magnetic fields from atmospheric electricity and magnetism; people are exposed to fields from household appliances without apparent effect; no harm has been observed from transmission lines up to 765 kV in the United States since 1969; no effects have been seen in studies of U.S. linemen who worked on 365-kV lines; and animal experiments so far have demonstrated no effects in the range of normal exposures found under transmission lines. From this experience there is good reason to believe that exposures to electric fields from transmission lines up to 765 kV would not produce harmful biological effects.

The next step, usually a long-term effort, is to establish and implement whatever research program is needed to determine if there might be any subtle and undetected effects associated with the given technology and, if so, what the specifics and exposure-response relationships might be. The latter information is useful so that control measures can be used if necessary to minimize effects in a cost-effective way and to allow decisions of risk acceptance based on risk-benefit considerations.

EPRI and ERDA are supporting research on biological effects of electric fields at an annual rate of about $3 million. Decisions on the adequacy of support levels for research are necessarily subjective. In our view, the combined EPRI–ERDA funding is adequate, judged from the significance of any effects that may be uncovered and their relative importance compared with environmental and health problems associated with other aspects of energy production and use.

The possible effects from high-voltage transmission lines include the production of ozone, audible noise, shocks, and biological effects of electric fields. Ozone production has been accepted as being insignificant. Audible noise and the possibility of shock can be reduced to nuisance levels and below by proper engineering. The question of biological effects is more difficult to deal with.

Living organisms have within them naturally occurring electric fields and currents. These play an important role in physiological mechanisms such as those involved in neural and muscular activity, tissue growth and repair, and cell membrane function. It is quite reasonable to question whether or not mechanically generated external fields can affect such functions. Fundamental studies of possible interactions are of great importance for an understanding of neurobiology, physiology, and certain behavioral mechanisms. However, from the practical standpoint of decisions about transmission lines, the issue is not whether these electric fields can produce biophysically detectable changes, but whether they would produce harmful effects in individuals exposed.

No experiment, no matter how large or how well designed, can tell us that electric fields will produce zero biological effects. What we do hope to accomplish is, first of all, to repeat the usual exposures under carefully controlled conditions to provide more reliable data than are now available. Then we plan to identify any of the subtle effects that could occur from high-voltage transmission lines and, if found, relate them to effects on humans. This should help in determining if and at what point the risk from increasingly higher transmission voltages becomes significant enough to be a limiting factor. The benefits from the use of high voltages against which any risks must be weighed are economic (major reductions in transmission costs) and environmental (saving right-of-way space). These are critically important contributors to sorely needed efficiency in today's otherwise bleak energy outlook.

There are those who believe that the benefits from the use of higher voltages are not worth the possibility of subtle biological effects that may be impossible to rule out by experiment. While our research, together with that of others, can provide information to help evaluate the risks and benefits, the final resolution involves public-political decisions. As an example, the New York State Public Service Commission is conducting extensive hearings on the health and safety aspects of high-voltage overhead transmission facilities. Although the hearings are still in progress, the commission has authorized the start of construction of a 765-kV line in New York State. We agree that experience thus far supports a reasonable contention that high-voltage lines can be operated with due regard for the public safety and welfare.

Cyril Comar, Director
Environmental Assessment Department
Energy Analysis and Environment Division

Authors and Articles

■ The automobile, the SST, and high-voltage transmission. Unquestionably they are technological advances. Unquestionably they have produced side effects. Undesirable side effects have been claimed for each, urgently and emphatically. But with high-voltage transmission at least, the preponderance of research so far does not support the contention. In **"Concern Overhead"** (page 6), EPRI's **Harry Kornberg** discusses the issues and reviews the scientific evidence.

Kornberg is in charge of a $2 million research effort specifically addressing biological and other ecological effects of high-voltage electric fields, and he is manager of the overall program on ecological effects in EPRI's Environmental Assessment Department. Last summer he visited laboratories in England, France, Germany, and Sweden to consult with European researchers studying the biological effects of electric fields. This month he is reviewing EPRI's program with visiting Soviet scientists at Battelle, Pacific Northwest Laboratory, where much of the Institute's research on this subject is being conducted.

Kornberg spent several years with Battelle-Northwest as a manager and then as a consultant in environmental and life sciences research before joining EPRI in 1974. For 20 years, beginning in 1948, he managed the Hanford biology program, a major research operation sponsored by the Atomic Energy Commission's Division of Biology and Medicine. Kornberg holds a PhD in bio-organic chemistry from the University of Texas and has written more than 100 scientific papers, books, and special R&D reports.

■ **"Halden: EPRI's Window on the Nuclear World"** (page 14) is primarily an exposition of what EPRI is doing and why at that small town in southern Norway. But **Garry Thomas,** EPRI's first technical representative there, also recounts some of his family's impressions from their trip abroad as he reviews the objectives and progress of EPRI's participation in the international Halden Reactor Project.

After earning a bachelor's degree at San Jose State University and doing graduate work in nuclear engineering at the University of California, Thomas developed a specialty in experimental irradiation operations and evaluations during eight years at General Electric Co. He was an experimenter on 22 transient overpower irradiations at an AEC test reactor in Idaho. He also helped establish a method of comparative analysis of LMFBR safety tests performed by Argonne National Laboratory for the fast flux test facility.

This background, together with a family goal of spending a year or two working in Europe, made Thomas a natural when EPRI's Nuclear Safety and Materials Department needed a representative at Halden. He joined EPRI in July 1974, six months before going to Norway to supervise EPRI's test irradiations in a program to improve fuel performance.

During that time Thomas and his wife took Norwegian lessons, graduating, he says, "at about prekindergarten level." However, Thomas's contributions to the Halden experiments —as well as his observations of them— are at advanced postgraduate level.

■ It's easy to watch energy conservation take place, and even to measure it. Meter readings and load curves ultimately tell the story. It's another thing to identify people's different conservation motives, and it's still tougher to distinguish one from another in practice. What's most difficult is measuring the motives themselves, so as to project them over an entire utility system, for example, and assess the effect of a given conservation opportunity on that system. All these are the concerns of **Robert Crow,** writing on **"Energy Conservation: Behavioral Considerations"** (page 20).

Crow makes the useful, clarifying point that energy conservation is really a special instance of energy demand. Conservation motives therefore are demand influences, and putting numbers on them is a matter of demand analysis. This in itself involves Crow, who has managed EPRI's Demand and Conservation Program since 1974. The overtones of behavioral psychology also fit neatly with one of his profes-

Kornberg Thomas Crow Tassicker Schwab

sional interests, the theory of consumer behavior.

A former faculty member in the School of Management at the State University of New York at Buffalo, Crow has taught, consulted, and done research in the fields of regional growth, economic forecasting, and urban transportation planning. He holds a PhD in economics from the University of Pennsylvania.

■ The conference room is a familiar setting for research evaluation. The lab itself is another. The field test site is a third and far less frequent—or even possible—choice. But an EPRI advisory group hit on the possibility this year, and it could set a precedent. In **"Reactor Safety Tour"** (page 55), John Kenton, the JOURNAL's specialist for nuclear power, reports what was seen by the Nuclear Safety and Analysis Task Force in a meeting at Idaho Falls.

■ **Owen Tassicker** and **James Schwab** are in charge of one of EPRI's success stories, and they record its technical substance in: **"High-Intensity Ionizer for Improved ESP Performance"** (page 56).

The romance with the ionizer originated in its poor but honest beginnings: a small R&D firm seeking a sponsor for a promising new concept. That firm was Air Pollution Systems, Inc., in 1974. EPRI's Owen Tassicker sensed the promise and initiated a development contract to establish EPRI's sponsorship.

An EPRI project manager for three years, Tassicker was previously a member of the electrical engineering faculty at Australia's University of New South Wales for 12 years and an active international consultant for much of that time. With the perspective of that experience he observes, "It is positively uncanny how the ionizer has moved from bench to demonstration scale in only 30 months, so far without any scale-up problems electrically, aerodynamically, structurally, or mechanically. This never happens!"

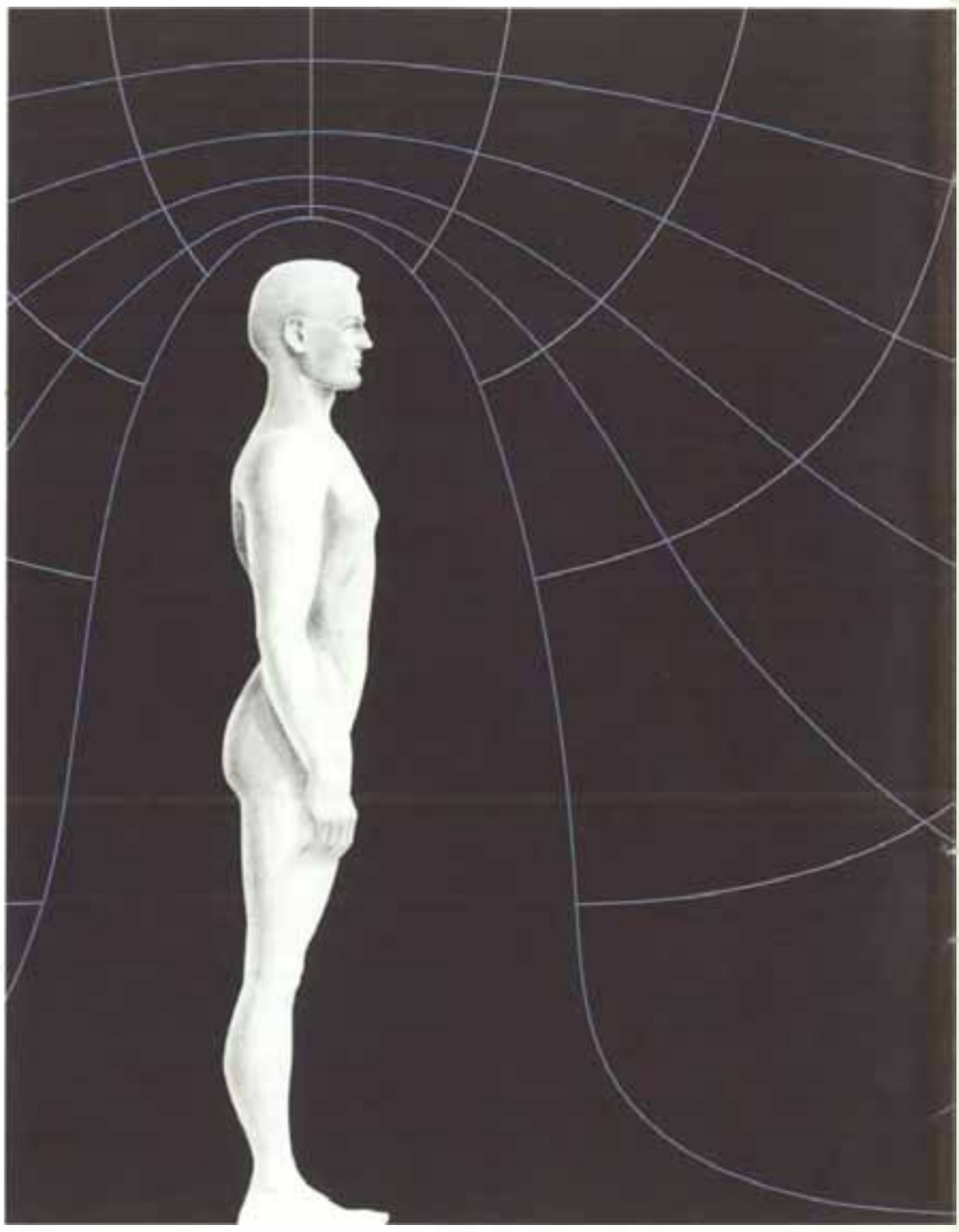
James Schwab, a co-inventor of the high-intensity ionizer and now APS senior vice president, acknowledges and welcomes the challenge, but he says it isn't all airy exhilaration yet: "EPRI has lots of expectations, understandably, and we have some of our own. There are times when it gets to be a heavy load." Still, Schwab likes it where he is, taking scientific ideas and doing the engineering analysis that will most quickly and cheaply determine commercial feasibility. That was the thread of his four years with Boeing Aerospace Co.—Schwab's first work after earning a BS in mechanical engineering at Tri-State College (Angola, Indiana)—and it characterizes what he has been doing for APS since 1973.

CONCERN OVERHEAD

by Harry A. Kornberg

As transmission line voltages have risen, so has concern over biological effects of exposure to electromagnetic fields. EPRI and ERDA are cooperating in extensive research to determine if there are such effects.

▫ An EPRI state-of-the-art feature

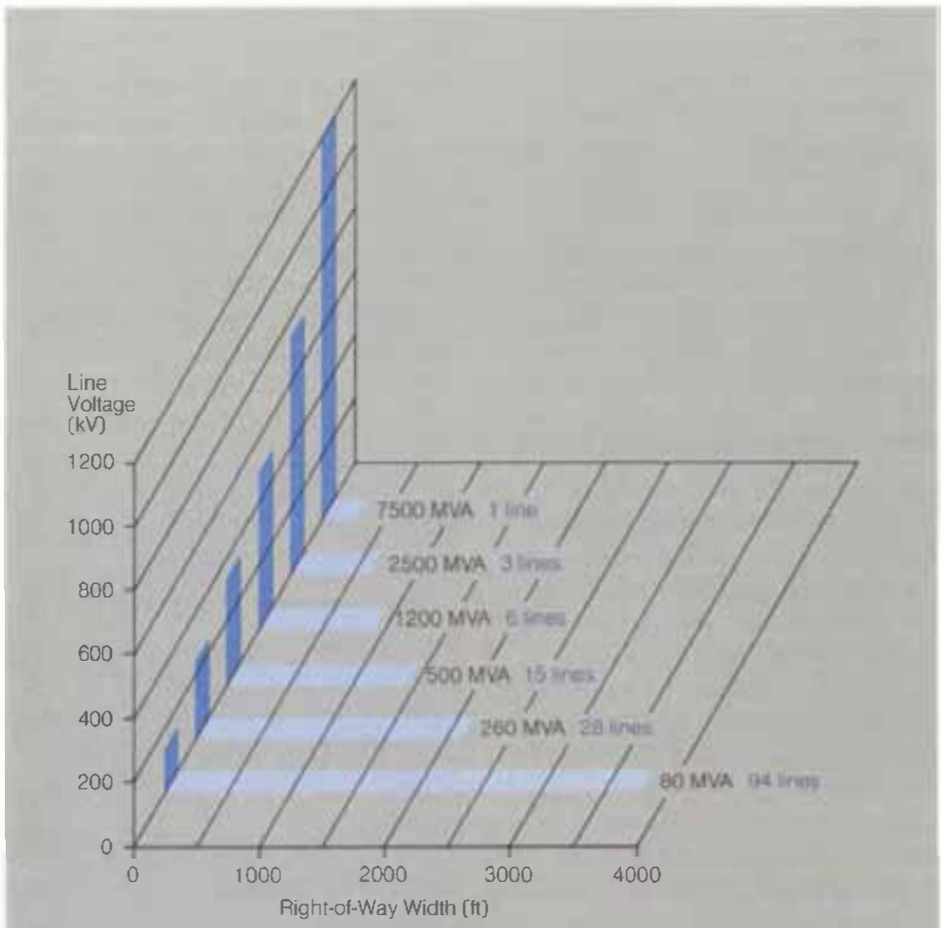


Harry A. Kornberg is manager of the Ecological Effects Program in the Environmental Assessment Department of EPRI's Energy Analysis and Environment Division.

Thousands of miles of overhead transmission lines that traverse the country are the superhighways of the electric utility industry—carrying the current that powers inventions ranging from a single light bulb to a national broadcasting network.

As demand for this essential power has increased, so has transmission voltage. It has been demonstrated that higher voltages can transmit more electricity over longer distances at less cost. For instance, a single 765-kV line can carry as much power as thirty 138-kV lines. The resultant conservation in land alone is substantial—a 765-kV line requires only $1/13$ the land area per kilowatt of capacity as its equivalent in 138-kV lines. And construction cost per kilowatt of the higher-voltage line is typically 10 times less. The benefits of higher transmission voltages include conservation of land, fuel, and funds, with utility customers enjoying more efficient, reliable service at lower rates.

There are more than 200,000 circuit miles of overhead transmission lines rated 138-kV or higher. The Federal Power Commission estimates that the 14,000 circuit miles of 500-kV and higher lines will increase to 24,000 miles by 1980 and to 42,000 miles by 1990. Experimental ac and dc lines in the 1200-kV range are also being tested. Without the use of high-voltage overhead transmission, U.S. utilities would be unable to supply at a reasonable cost the electricity required by the country's urban centers.



The higher the voltage of a transmission line, the more power it can carry and the less land and money needed for its construction. A single 765-kV line carries as much power as thirty 138-kV lines, requires $1/13$ as much land per kilowatt, and costs 10 times less to build. It would take ninety-four 138-kV lines to carry as much power as three 765-kV lines.

EPRI is exploring alternatives to high-voltage overhead transmission and a vigorous research program on underground transmission is under way. However, with the present state of the art, underground transmission costs from 12 to 16 times more than overhead. It is estimated that if all future transmission lines were to be placed underground, the cost of electricity to the consumer would rise 30–50%. If existing lines were also transferred underground, electricity bills would at least double.

EPRI is also investigating ways of generating power locally through fuel cells, which would place the power source near where it is needed and require only low-voltage distribution lines. But fuel cells are not expected to be available for some time and will be used primarily to meet peak requirements rather than base loads.

Concern over electric fields

It is evident, therefore, that we will be living with overhead high-voltage transmission lines at least through the end of this century. That being the case, it is important that the possible biological effects from exposure to electric fields generated by high-voltage lines be determined and understood. The U.S. utility industry has been supporting research on high-voltage effects since 1966 (through EPRI since 1974). EPRI is sponsoring some $2 million in such research, with cooperative work by ERDA of more than $1 million.

Public concern over high-voltage effects has been stimulated by hearings before the New York State Public Service Commission on the proposed construction of a 150-mile, 765-kV transmission line Testimony on the health and safety aspects began in February 1975, considering matters of ozone production, audible noise, induced electric shocks, and biological effects. Only the issue of biological effects has kept the hearings open. The possibility of biological effects has likewise been a key issue in hearings on a proposed 430-mile, ±400 dc line that would traverse portions of Minnesota and North Dakota.

Physics of electric fields

A grasp of some of the basic physics of electric fields helps in understanding effects that may occur. The intensity of an electric field at any point is described by the magnitude and direction of the force that would be experienced by a unit charge placed in the field at that point. If we imagine a charged object, such as a sphere, lines can be drawn representing forces between unit charges on the sphere and in space. These flow lines map the electric field. Lines per unit of area are directly related to the magnitude of the electric field intensity. The field becomes stronger as one approaches the charged object. This phenomenon occurs in a clothes dryer. Synthetic clothing picks up an electric charge when it rotates in the dryer, which causes the clothing to cling to itself and to nearby objects.

In mapping electric fields it is common practice to draw the lines of flow and the equipotential lines, which are perpendicular to the flow. When a conducting object, such as a person, enters the field, the field becomes distorted. The lines of flow per unit area increase as they are "displaced" by the object. And the more pointed the object the more it will distort the field, intensifying the charge.

The highest voltage transmission lines in the U.S. are nominally rated at 765 kV. Under a typical 765-kV line at its closest proximity to the ground, the field of intensity is about 8 kV/m at a measurement point about 1.5 m (5 ft) above the ground. A person standing on the ground in this field would have about 120 microamperes flowing through him, about $1/10\,000$ of the current flowing through a 100-W light bulb. Leakage currents from metallic household appliances cause 20–300 microamperes of current flow in grounded persons holding them. (The ANSI standard maximum leakage current is 500 microamperes for portable appliances and 750 microamperes for stationary appliances.) To perceive a current flow, 500 microamperes typically are required.

For a physical agent to cause biological effects there must be a transfer of energy from the physical agent to the living material. An electric field transfers energy by inducing currents in the body. A 60-Hz line alternates from a plus to a minus charge 60 times a second, causing a change in position of the plus and minus charges on and within the body. As the ac field changes polarity, the induced charges likewise change, which, in turn, causes

Table 1
ELECTRIC FIELDS (60 Hz) GENERATED BY APPLIANCES

Item	*Electric Field (kV/m)**
Electric blanket	0.25
Broiler	0.13
Stereo	0.09
Iron	0.06
Refrigerator	0.06
Hand mixer	0.05
Toaster	0.04
Vaporizer	0.04
Color TV	0.03
Coffee pot	0.03
Vacuum cleaner	0.016
Clock	0.015
Fluorescent light (office)	0.01
Electric range	0.004
Incandescent light bulb	0.002

*Measurements made 30 cm from appliance

body current to flow. Under certain conditions, a person standing under a 765-kV, 60-Hz line can perceive the field by the tingling of skin on a raised forearm.

Wavelength is the key

Energy is transferred to an object near a 60-Hz power line via the electromagnetic field generated by the line currents. The fraction of this energy transferred to humans is negligible compared with that transferred from other common sources of electromagnetic fields, such as television transmitters. The reason is that the amount of energy absorbed by an object is a function of the wavelength of the inducing field. For a given object, energy absorption becomes radically smaller as wavelength becomes longer. Thus, the energy absorbed by a person standing in a 60-Hz power line field (wavelength 5000 km) is approximately 10^{12} *less* than the energy that person would absorb from being in a 60-MHz electromagnetic field of equal intensity (wavelength 5 m), a frequency at which a television station may broadcast.

As the frequency of the electromagnetic field is increased, the wavelength is reduced to where it is comparable to the size of the object. Many typical biological tissues and organisms have dimensions comparable to a microwave wavelength (1 mm–1 m) and thus undergo resonant energy deposition at microwave frequencies (300 MHz–300 GHz). This physical property is at work in microwave ovens to enable virtually total transfer of the power in the electromagnetic field to the food, causing rapid heating. The process of resonant energy collection and dissipation is entirely different than that occurring at 60 Hz and is much more effective in energy transfer.

Infrared radiation has an even shorter wavelength than microwave, between a few tenths of a millimeter and less than a micrometer. This is in the size range of living cells. Such radiation is readily absorbed by the skin and is felt as warmth.

Energy from visible light is absorbed by specific receptor bodies in the retina of the eye and enables us to see. This radiation is in the range of tenths of micrometers. Shorter still is the ultraviolet band, with a wavelength the dimension of certain molecules in the skin that become chemically transformed as a result of energy interchange, causing sunburn or tanning.

So humans, whose height is well under 2 m (6.5 ft), can interact effectively with many types of electromagnetic radiation, but cannot do so with radiation from 60-Hz transmission lines with a wavelength of 5000 km. Then why the concern and extensive research on biological effects? For two reasons: Although minute, some energy is absorbed by biological matter from a 60-Hz field; and there are reported incidents of biological effects claimed to have been caused by high-voltage fields.

Reported effects

Reports of such biological effects that are receiving attention come from the Soviet Union. They describe unfavorable, nonspecific disturbances—loss of appetite, listlessness, diminished sex drive—in switchyard workers occupationally exposed to high-voltage gradients for long periods. As a result, the Soviet government has set time limits for exposure to electric fields greater than 5 kV/m.

Only one other similar experience is known. In Spain, five of eight switchyard workers, transferred to a new 500-kV power station, reported headaches, fatigue, and loss of appetite.

In the U.S., carefully conducted medical and psychiatric examinations were given over a nine-year period to 10 utility linemen who worked on energized lines and were exposed to electric fields of various intensities. None of the 10 showed any changes in physical, mental, or emotional characteristics in several thorough examinations given during the nine years.

An analysis was made of the medical records and medicine purchases of two groups of French people of the same social class, one living within 25 m of a 200-kV and a 400-kV transmission line, the other residing at least 120 m distant. No difference was revealed between the two groups in the amount of their medical care and drugs or in the frequency of medical examinations.

Experiments involving field strengths up to 20 kV/m have been performed on volunteer human subjects in West Germany and Sweden under carefully controlled conditions. No physiological or biochemical changes were observed in the German study. And no changes were evident in test performance and subjective responses in the Swedish investigation of psychological effects.

A direct correlation cannot be made between these studies and the Soviet experience since maximum exposure in the studies was three hours, while the Soviet reports indicate the syndrome developed after prolonged exposure. Yet extended exposures of linemen and switchyard workers elsewhere have failed to produce a similar syndrome. Attempts to explain the difference have suggested that environmental factors such as noise, noxious vapors from plants, oil fumes, chemicals from switchyard equipment, and possible disease may have been the cause. To determine whether one or more such factors are accountable for the effects would be difficult since these environmental agents change with time. One method for verifying the Soviet results is by using experimental animals.

Animal and human experiments

The most extensive research on biological effects at power line frequencies

Table 2

AMERICAN AND WESTERN EUROPEAN TESTS OF ELECTRIC FIELD EFFECTS

(50 Hz and 60 Hz)

Subject	*Exposure*	*Indicator*	*Result*
7 humans	7.5 kV, 2.5 kV, 27 kV; 30-min.	EKG	No effect
525 humans	Fields within 25 m of 200- and 400kV line; fields beyond 125 m for control group; long-duration	Checkups by physicians; use of medicine; medical histories	No significant difference observed between subjects and control group
10 males 10 females	25 kV/m	Psychological test; subjective responses	No statistical difference observed in test performance; some discomfort reported by a few subjects; subjects also influenced by weather
Farm workers and livestock on 18 farms	Fields from 765-kV line	Questionnaire response	No significant effect
10 American linemen	Fields encountered in normal line and bare-handed work	Physical examination; cardiovascular, EKG, kidney, visual, auditory, emotional status	No effect
10 humans	1 kV, 15 kV/m; intermittent, 45 min	Physical examination: EKG, EEG, pulse, blood pressure, reaction time	No significant change; small decrease in reaction time
6 humans	1 kV/m, 15 kV/m, 20 kV/m; alternating, 45 min	Physical examination: EKG, EEG, blood pressure, reaction time	No pathological changes

is being done by the U.S. Navy in connection with its Project Seafarer. (Seafarer is the Navy's proposed communication system of several hundred kilometers of buried cable, operating at a frequency of 30–90 Hz. (The network is designed for communication with submarines.) Although the frequencies are in the 30–90 Hz range, the voltage gradients are much lower (0.01–0.02 kV/m) than those from high-voltage lines, while the magnetic fields are higher (2–3 G). Some 40 separate experiments have been performed by various investigators using a variety of biological materials, from soil microorganisms and fruit flies to cows and humans. The biological effects looked for ranged from genetic to behavioral.

All results except one were negative. Some of the several human subjects exposed for 24 hours to alternating magnetic fields of 30–90 Hz experienced a rise in their serum triglycerides 24–48 hours after exposure, with a subsequent return to normal. Continued high serum triglycerides is a condition sometimes associated with propensity to heart disease. Transient increases are not considered significant. The scientist reporting this work pointed out that the increase could have been due to forced changes in personal living habits, such as diet and confinement. However, this observation led a West German scientist to investigate whether high-voltage fields as well as magnetic fields would cause the same effect in humans. Volunteers were exposed to 20 kV/m for three hours. The results indicated no increase in serum triglycerides.

More recent animal research in the Soviet Union describes a variety of physiological responses attributed to electric field exposure. But since details of these investigations are not given in the published reports, it is impossible to make an evaluation. Adverse biological effects in laboratory animals exposed to 60-Hz electric fields have been reported recently by one group in the U.S. However, similar experiments performed in the U.S. by others have shown no such effects.

Such conflicting results have called for further research to resolve the differences. It is essential that research of this nature be conducted under carefully controlled laboratory conditions and precise procedures. The transfer of energy from electric fields to living matter is minute, even at levels 10 times that which can be encountered under transmission lines. If there are effects, they will be subtle and difficult to recognize, so great care in experimental design and control is crucial. If, for instance, the experimental electrodes are not specially designed and made, ozone can be generated that could swamp subtle effects and be misinterpreted as an effect of the field. Effects can also be attributed to an electric field that are actually caused by a trivial mediator. For example, when experimental animals are exposed to 100 kV/m (more than 10 times the maximum that can be encountered underneath transmission lines), their hair vibrates at the frequency of the field. This hair stimulation is readily felt by the animals and generally excites them to increased activity, which may easily be mistaken for changed

metabolic rate resulting from the electric field.

EPRI–ERDA investigations

In long-range tests being performed for EPRI by Battelle, Pacific Northwest Laboratory, groups of Hanford miniature swine, a specially bred experimental animal that serves as an analog for humans, will be continuously exposed to a voltage gradient of 30 kV/m (a level at which hair stimulation does not occur in these animals). Guidance on the parameters being measured in these animal experiments is coming mainly from observations on rodents in parallel tests sponsored by ERDA. These cooperative EPRI–ERDA tests on large and small animals represent the most comprehensive research so far undertaken on the biological effects of high-voltage fields. The research team is made up of behavioral scientists, electrical engineers, mathematicians, hematologists, physicists, physiologists, and pathologists. Both EPRI and ERDA are optimistic that some definitive answers will be forthcoming within a couple of years.

Some answers have already come in from experiments on high-voltage effects on vegetation. In tests performed for EPRI by Westinghouse Electric Corp. and Pennsylvania State University, it was determined that leaf tip damage occurs at between 20 kV/m and 22 kV/m for pointed leaves—about 1% of the leaf is damaged, but photosynthesis is not affected. Extended exposure up to 50 kV/m caused no damage, however, to round leaves. And no effect on plant growth was observed.

The Penn State investigators also looked into the effects on chicken eggs. They found no effect on hatchability and that exposure of chicks to 80 kV/m for 30 minutes had no effect on growth or development. Exposure of chicks for three weeks to 80 kV/m resulted in a temporary increase in growth rate, but this did not occur with exposure at 40 kV/m. Heart rate increased from exposure at 40 kV/m and 80 kV/m, but not at lower gradients.

EPRI is also supporting research in effects on bees. A beehive is a complex social structure and in many respects is an excellent system for determining subtle effects. The interdependence of all members of a colony—queen, drones, and workers—in their production of honey makes the beehive a good model for studying effects on ecosystems. In this field experiment, beehives have been placed on a small hill between two 765-kV transmission towers owned by Commonwealth Edison Co. Possible effects are being carefully monitored.

A laboratory study has been completed by IIT Research Institute for EPRI on the effects of electric fields on pacemakers implanted in baboons. It was found that electric and magnetic fields from overhead lines will not affect the majority of pacemakers. Interference with pacemaker operation can occur in rare cases where highly sensitive pacemakers are implanted in uncommon configurations. In these cases the pacemaker reverts to a constant pacing mode while in the electric field and then returns to normal operation when out of the field. This "reversion" is not considered significant by most doctors. Nonetheless, results of this study will be discussed by cardiologists and representatives from the National Heart Institute, the National Bureau of Standards, and the Food and Drug Administration at a workshop sponsored by EPRI this fall.

Since the U.S. study of effects on humans exposed to electric fields involved only 10 utility linemen, EPRI asked Equitable Environmental Health Associates to assess the feasibility of a similar but much larger study. EEHA reported it would be feasible, but difficult. Two of the difficulties: lack of knowledge of any physiological effect attributable to the electric field and lack of knowledge of exposures. EPRI's biological research program is expected to uncover the former, if it exists. On the latter, EPRI is having General Electric Co., as part of Project UHV, develop a portable field meter that can be worn by linemen and switchyard workers to determine exposures.

To further strengthen its investigations of high-voltage effects, EPRI in 1975 formed the Advisory Committee on Biological Effects of Electric Fields to assist in developing plans and priorities for continuing research and for reviewing research in progress. The committee consists of 10 distinguished scientists, engineers, and representatives from government and industry.

As it is

This is what can be said about the biological effects of electromagnetic fields at 50 Hz or 60 Hz:

- Reports from the Soviet Union of effects in switchyard workers cannot be confirmed from examinations of similar workers in Canada, England, France, West Germany, Italy, or the U.S.

- No experiment thus far has clearly established that electric fields even 20 times as high as those encountered under 765-kV transmission lines can cause a biological effect of significance.

- If electric fields can cause biological effects, it appears that they will be subtle, possibly elusive, and extremely difficult to identify.

If indeed there are such effects, EPRI's extensive research program, together with ERDA's parallel efforts, is applying the best scientific methods to identify them.

Details of EPRI's research program on biological effects of electric fields follow.

Table 3

EPRI RESEARCH PROGRAM ON BIOLOGICAL EFFECTS OF ELECTRIC FIELDS

Project and Contractor	*Funding and Duration*	*Objective and Current Status*
Environmental Assessment Department		
RP129; Ecological Influence of Electric Fields; Westinghouse Electric Corp.	$376,000 May 1974–March 1977	*Objective:* Investigate the effects of electric fields at power line frequencies on plants and chicken embryos at Pennsylvania State University. *Status:* Defined and simulated electric field environment under power lines. Chicks exposed to 40–80 kV/m during incubation show temporary increased growth rate. Plants with pointed leaves show tip damage about the first week of exposure. No effect on plant germination at 50 kV/m. No effect on egg hatchability or embryo activity at 50 kV/m.
RP679; Effect of 60-Hz Electric and Magnetic Fields on Patients With Implanted Cardiac Pacemakers; IIT Research Institute	$110,000 September 1975–December 1976	*Objective:* Investigate the effect of 60-Hz HV-electric fields on cardiac pacemakers implanted in baboons and translate any effects to the human case. *Status:* In rare cases "reversion" occurs but is not considered significant.
RP799; Electric Field Effects on Large Animals; Battelle, Pacific Northwest Laboratory	$1,200,000 March 1976–February 1978	*Objective:* Study effects of chronic exposure of Hanford miniature swine to HV electric fields. Test animals will be exposed from conception through duration of project to field levels greater than those found under power lines but below perception levels. Constant clinical assays will be taken to identify even subtle effects. *Status:* Exposure facilities are under construction. Electrode exposure system is being tested. Operating procedure and safety rules for exposure system are prepared. Breeding protocols for two generations of animals have been designed.
RP857; Biological Effects of Electric Fields—General Support Study; IIT Research Institute	$130,000 August 1976–July 1977	*Objective:* Update state-of-the-art study initiated in earlier project (RP381), abstract foreign literature and translate key documents, provide technical support for the EPRI HV effects program, determine the applicability of various Seafarer data to power line environments, and study internal currents and dosimetry associated with HV fields. *Status:* Foreign literature review and abstract translation is near completion. Translation of key documents is under way. Domestic literature is being reviewed.
RP934; Field Evaluation of Effects of HV Power Lines; Bioconcern, Inc.	$122,000 August 1976–December 1978	*Objective:* Investigate effects of exposure of honeybees to maximum fields under a 765-kV line. Study honey and wax production, reproductive success, hive health, activity, and behavior as indicators of neurological effects. *Status:* Feasibility study completed and hives established under contract TPS76-630.
TSA76-79; Basic Introduction to Effects of HV Power Lines, IIT Research Institute and NUS Corp.	$20,000 May 1976–October 1976	*Objective:* Prepare a primer to inform the public on facts relating to effects of electric fields. *Status:* In preparation.
TPS76-639; Feasibility Study: Epidemiology of Linemen and Switchyard Workers; Equitable Environmental Health, Inc.	$17,000 April 1976–September 1976	*Objective:* Assess feasibility of conducting epidemiological studies on workers routinely exposed to HV fields. *Status:* Preliminary report has been reviewed.

Note; An international workshop on biological effects of electric fields is under consideration.

Project and Contractor	*Funding and Duration*	*Objective and Current Status*
Related HV Projects in Electrical Systems Division		
RP68; UHV Transmission; General Electric Co.	$15,500,000 January 1967–December 1979	*Objective:* Investigate corona phenomena, insulation, and electric field effects for voltages up to 1500 kV on three-phase test line. *Status: Transmission Line Reference Book—345 kV and Above* has been published.
RP566; Study of Electrostatic and Electromagnetic Effects of UHV Lines; General Electric Co.	$385,000 January 1976–December 1977	*Objective:* Accelerate UHV research under RP68, study methods for reducing electrostatic fields at ground levels, and investigate electrostatic effects due to transients and electromagnetic effects. *Status:* Studied various underbuilt energized conductors and grounding systems. Developed mathematical predictive equations for effects of underbuilt energized conductors and grounding systems. Constructing underbuilt energized conductors at various voltages.
RP753; Model Field Measurements; Ohio State University	$105,000 January 1976–July 1977	*Objective:* Determine if miniature model substations are valid predictors of electric field strengths in substations and develop small measuring devices. *Status:* Model of existing 345-kV substation built and tested. Tests demonstrated that an energized scale model is a valid analog design tool for an ac substation and can be used to map and modify the electric field. Further work is under way to develop a simplified model for ac substations and to expand its range of use.
RP1097; Model field measurements; Ohio State University	$110,000 August 1977–June 1979	*Objective:* Similar to RP753 for HVDC substations *Status:* Contract in negotiation.
RP742; Induced AC Potentials in Pipelines; IIT Research Institute (with American Gas Association)	$300,000 January 1974–December 1977	*Objective:* Prepare tutorial handbook on induced ac potentials on pipelines. *Status:* Prepared outline and supporting materials. Field verification under way.
RP104; HVDC Transmission; Bonneville Power Administration	$866,000 January 1974–June 1976	*Objective:* Research corona phenomena, insulation, electric fields, and maintenance practices for dc lines to ±600 kV. *Status:* Project completed and design reference book to be released shortly
RP430; HVDC Transmission Between ±600 kV and ±1200 kV; Hydro-Quebec Institute of Research	$444,000 January 1975–December 1977	*Objective:* Study corona phenomena, insulation, and power supply requirements for contaminated insulator research. *Status:* Insulation and power supply studies completed; continuing long-term corona tests. Extension requested to expand electric field studies.

Halden: EPRI's Window on the Nuclear World

by Garry R. Thomas

A personal account of what is being done at the Halden Reactor Project in Norway, why EPRI is participating in that international venture, and what it was like to spend 18 months in Norway.

□ An EPRI program feature

Garry R. Thomas is project manager for test reactors in EPRI's Nuclear Power Division, Systems and Materials Department

Regardless of the direction my future career may take, I will always look back on the 18-month period of February 1975 through July 1976 as one of my most challenging and enjoyable experiences—both from a technical and a personal veiwpoint. That was when my wife, two children, and I pulled up stakes and moved to Halden, a small town in the southeastern corner of Norway.

Why were we there? I had become EPRI's first foreign site representative, and my assignment was the Halden Reactor Project. HRP is a small but very impressive international center for nuclear power research with a staff of 170 that includes 60 technical specialists, about 20 of whom are non-Norwegians (such as myself) on temporary assignment. Despite—or more probably because of—its relatively small size, HRP has developed a reputation for successfully tackling extremely complex in-core studies of nuclear fuel rod behavior, using the highly versatile Halden boiling heavy water reactor (HBWR). Heavy water is the common name for deuterium oxide (D_2O), which is similar to ordinary water but the hydrogen has been replaced by its isotopic relative, heavy hydrogen, or deuterium, twice the weight of ordinary hydrogen.

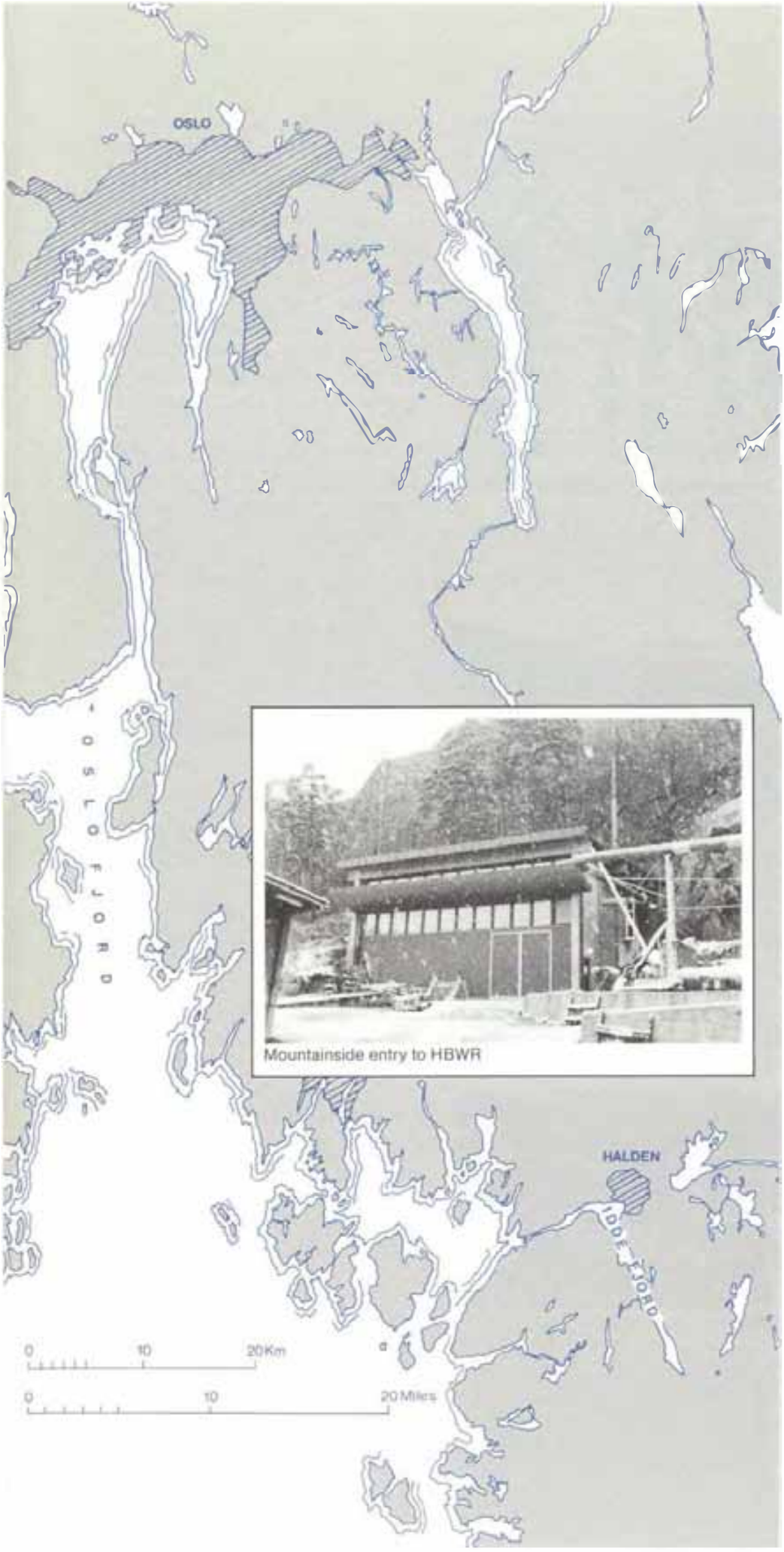
HRP is now international; it is sponsored by the 24-nation Organization for Economic Cooperation and Development (OECD) and operated by Norway's Institutt for Atomenergi—the official agency for nuclear power research in Norway—on behalf of the national nuclear agencies of those 9 OECD countries that jointly fund HRP: Austria, Denmark, Finland, West Germany, Italy, Japan, Netherlands, Norway, Sweden, plus EPRI and three associate members. (EPRI is the only nongovernmental body that is a full signatory member.) The associate members are Combustion Engineering, Inc., General Electric Co., and the U.S. Nuclear Regulatory Commission. The project is governed through a representative board of directors.

HRP history

Norway, through the Institutt for Atomenergi (IFA), was a pioneer among smaller nations in nuclear reactor technology; its first reactor, Jeep (a nuclear properties research reactor at Kjeller, near Oslo) became operational in 1951. By the second half of the 1950s, IFA was developing concepts for using reactors to produce power for Norwegian industrial and residential consumption. Because of the plentiful natural hydropower available for electricity generation, these efforts were geared toward using nuclear power to produce process heat, primarily to support Norway's heavy industry and in particular, one of its major exports, processed wood products. At the same time, the ready availability both of large, highly stable rock formations (Norway has been described as consisting of 80% bare rock, 27% forest, and 3% arable land) and the well-developed Scandinavian technology of shaping and moving that rock (e.g., cutting tunnels about 32 km (20 mi) through solid rock for moving water to areas of greater hydroelectric potential), led IFA to consider using rock mountains for secondary nuclear containment, that is, emplacing reactors underground in solid rock.

Thus the HBWR was built deep in the side of a cliff, 92 m (300 ft) back from the cliff face and directly across the road from the large Saugbrugs paper mill. This location is only about a kilometer (half a mile) from the center of Halden and less than 50 m (150 ft) from the closest residential properties atop the mountain containing the HBWR. The reactor became operational in 1959. Since then, despite its heavy research load, the HBWR has continued to fulfill its original process heat production objective by supplying, when on line, a small portion of the steam required by the adjoining paper mill.

The overall initial objective of the HBWR and the Halden project that grew up around it was to gain practical experience in the design, construction, and operation of naturally circulating, boiling



Mountainside entry to HBWR

heavy water reactors. To this end, the design of the HBWR primary containment (the reactor pressure vessel) provided many instrumentation monitoring positions through multiple, conveniently located access ports. This permitted a versatile and detailed monitoring of overall reactor operating characteristics.

For the first several years of HBWR operation (1959–1963), the effort concentrated on attaining these objectives. However, the Norwegian government turned over administrative control of the reactor to the OECD-sponsored HRP. For with the changing environment—both within Norway (which de-emphasized its long-term commitment to the use of nuclear power) and with the worldwide growth of light water reactors—there was no longer a strong need to continue development of heavy water reactor technology at Halden. Instead, as the years passed, the built-in advantages of ease of access to the HBWR core through its multiple access ports in the reactor vessel head rapidly made it one of the world's most versatile reactors for performing detailed, closely monitored experimental studies of individual LWR fuel rod behavior. (The differential effects of studying such behavior in heavy water versus ordinary light water at the same temperature and pressure are inconsequential.)

By 1967, the HRP objectives had shifted strongly toward emphasizing study of water reactor (mostly LWR) fuel performance in general. Activities centered on in-core instrumentation development designed to increase the ability to observe such performance in detail at levels never before achieved. These efforts, taking advantage both of the easy accessibility to the HBWR core and of a creative staff composed of a permanent cadre and temporary members on loan from participating organizations, topped by a truly master-craftsman machine-shop capability, created an unusual environment for studies involving highly detailed control and monitoring of the behavior of nuclear fuel rods during power operation. At the same

HALDEN: A HISTORICAL TOWN

The town of Halden is located in one of Norway's major farming areas, among rolling, rocky hills broken by forests, farmland, and marshes. It is on the shores of Idde Fjord, a long and narrow offshoot fjord near the base of the much larger Oslo Fjord, which stretches some 100 km (60 mi) north to the Norwegian capital, Oslo. The Norwegian word *fjord* refers to any relatively long saltwater bay extending inland from the open sea, not the typical tourist interpretation of towering mountains falling steeply into a narrow, deep bay. While this picture is true of fjords on the western coast of Norway, the word is more general.

The Idde Fjord, generally a kilometer or so wide, is a section of the Norwegian-Swedish frontier. The major highway between Norway and the rest of Europe passes about 10 km (6 mi) west of Halden on its way north to Oslo and south to Sweden over a spectacularly beautiful bridge spanning the Idde Fjord at a point that is everyone's classic idea of a Norwegian fjord.

Halden, which is also a main rail junction, is nestled in a valley with the Tista River flowing through the center of town into the Idde Fjord. It has a commercial harbor, but the main local industrial activities center around the large Saugbrugs paper mill on the Tista, upstream from the center of town. The present population of Halden and its surrounding farming and suburban areas is about 27,000.

This region has been populated virtually since the dawn of recorded history. It has been continuously cultivated for thousands of years, with numerous traces of early history remaining in hundreds of graceful rock carvings, great longboats, and burial mounds—all within a short distance from Halden.

Geographically, Halden is situated at a land bridge, important in more recent history, that crosses from Sweden to Norway with the Oslo Fjord and the North Sea immediately to the west and a great expanse of dense, marshy forest to the east. This forest was nearly impassable for large groups on foot or on horseback. For nearly 300 years (1536–1814) Norway was a loosely connected part of a joint kingdom ruled from Copenhagen, and Halden was the scene of frequent battles between the Swedish and the Danish–Norwegian kingdoms. Because of Halden's ability to withstand Swedish attacks, it was granted the privileges of a town in 1665, and because of its military importance in blocking that crucial land bridge, a large fortress, the Fredriksten, was erected on a high bluff about 120 m (400 ft) above the town of Halden. This fortress still proudly dominates the city's skyline. It was never captured in armed conflict—not even during the Great Nordic War of 1716 when Halden was set aflame by its own inhabitants to drive out an occupying Swedish army, nor in the siege of 1718.

Early rock carvings

Bridge over the Idde Fjord

The Fredriksten fortress

Living in Norway

When I arrived in Halden in February 1975 with my wife Linda, my son Jory, and my daughter Niña, we did not have a housing problem because the Halden Reactor Project has its own modern condominium apartments.

We had looked forward to our sojourn with a great deal of positive anticipation although we knew there would be an adjustment in moving from one culture to another and from the large, cosmopolitan San Francisco Bay Area to the small-town—rural environment of Halden. My wife and I prepared for our trip by studying Norway and its culture and took lessons in the Norwegian language, graduating at a prekindergarten level.

Although much of our preplanning was aimed at reducing the expected culture shock, the shock was still there.

We moved overnight from relatively warm and light California to a dark and definitely cold Halden in winter. Norway has very long winter nights, compensated for by delightfully long summer days.

As a family, we found the adjustment period lasted about four months, but we grew to love the much more relaxed, outdoor-oriented lifestyle of the Norwegians. Jory, immersed in a total Norwegian environment at Sentrum School in downtown Halden, rapidly came to the point where Norwegian was his first language, and English was used only at home. The conversion was so complete that to our amazement he even spoke Norwegian when he talked in his sleep. Niña, too young to go to school, socialized with the neighborhood children, most of whom were from Halden Project families, some foreign like us and others Norwegian. As a result, she ended with a universal language used by all the younger children, composed of English, Norwegian, Danish, German, and a touch of Brazilian. My wife and I finally progressed from prekindergarten to kindergarten-level Norwegian.

There were many other adjustments as well, such as a significant change in diet. Norwegian cheeses are plentiful and excellent, and my daughter and I even mastered a taste for Geitöst, a strong goat's milk cheese. We also discovered that although prices are high in the U.S., it is not the most expensive place in the world to live: many basic commodities (e.g., food and clothing) are priced significantly higher in Norway (and in Scandinavia in general) than in the U.S.

The 18 months went by unbelievably quickly, and we were on our way home after a truly wonderful experience, having become much more aware of the similarities and differences between other cultures and our own.

time, HBWR and its associated data-acquisition system displayed a broad capability for accepting many highly instrumented experimental assemblies, or rigs, so that a typical core loading at present may contain as many as 45 experimental assemblies out of a total of 60; in other words, as little as 25% of the core may be composed of standard driver fuel assemblies. From 45 such experimental rigs, more than 500 individual instrumentation signals can be monitored simultaneously.

The thrust on improved in-core instrumentation continues, with the result that HRP has been able to maintain a leading role in the development of highly sensitive instrumentation for the in-core monitoring of fuel rod behavior. For example, the present zenith of HRP's operational experimental assemblies is the three-rod overpower-diameter rig. While at power in the HBWR core, this rig can simultaneously:

- Maneuver power levels in three rods, independent of HBWR core power, by a factor of almost two and over a wide range of time dependencies
- Measure the resultant rig output power through use of slow- and fast-response, static and movable neutron detectors; and combined coolant flow and temperature measurements
- Monitor at any given time all three rods for fuel rod cladding length changes to within 0.0025 cm (0.001 in) and fuel rod cladding diametral changes along the entire fueled region of the rod to within 0.013 cm (0.0005 in)
- Sip the coolant continuously for presence of fission products indicative of fuel rods failing in the rig
- Measure, in special cases, fuel rod internal gas pressure, fuel stack length changes to within 0.0025 cm (0.001 in), and fuel stack centerline temperature

EPRI participation in HRP

Early in EPRI's history, the Nuclear Power Division felt the need to be formally associated with the worldwide nuclear power community, particularly with the European and Japanese sectors, as a method of promoting a greater exchange of information in the economically important area of reactor fuel performance. HRP offered EPRI the first important opportunity for such an association, with two significant advantages for joining:

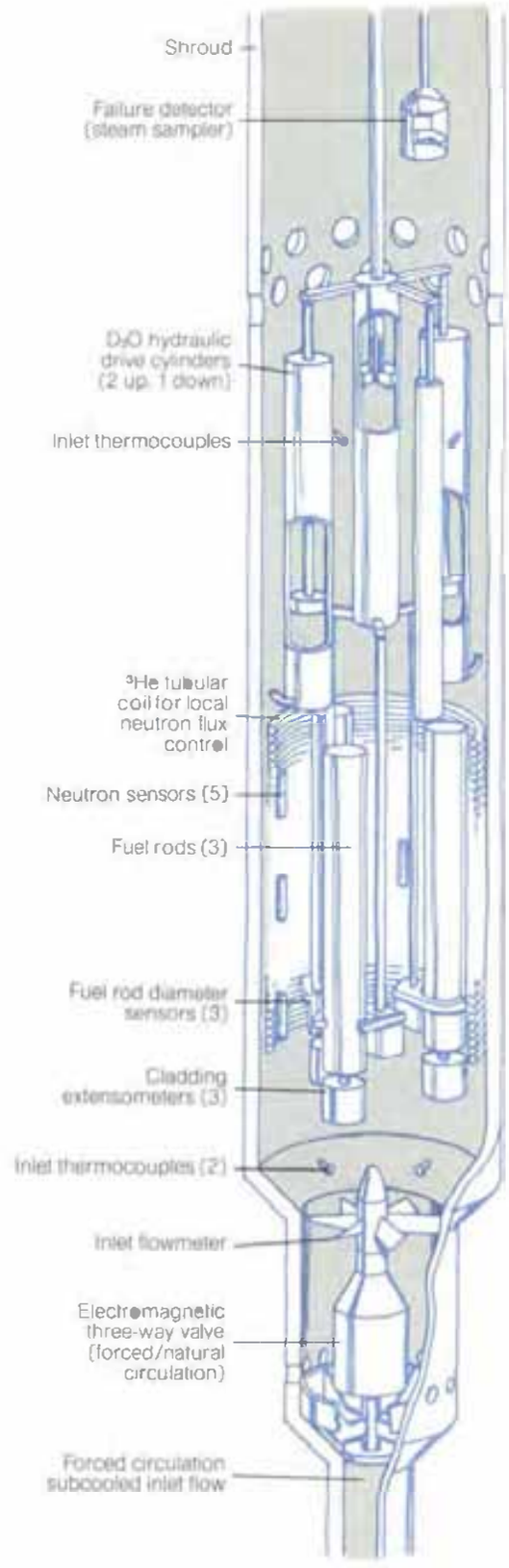
- Through HRP, EPRI would step into an existing international nuclear community having OECD sponsorship and the active involvement of more than a dozen members from around the world.
- EPRI would participate in an unusually qualified research group, a world leader in the experimental evaluation of nuclear fuel performance.

This early involvement in the international project provided a base for initial contacts that have either led directly to or greatly facilitated EPRI's formal participation with several European and international research and industry groups, such as contracts with Sweden's Studsvik Inter-Ramp and Over-Ramp projects (RP507 and RP-1026); technical exchange agreements with Sweden's nuclear industry giant, Asea-Atom Co.; and with The Utility Group (TUG), a working group of eight European utilities in seven countries.

EPRI joined HRP in January 1974 and is currently operating under its second three-year agreement covering participation (RP216). EPRI membership in the project permits EPRI and utility members to use the information generated by the HRP base program and results reported in the formal HRP documentation. To date, more than 150 of the specialized, highly instrumented experimental rigs have been irradiated in the HBWR, and more than 200 HRP reports have been issued.

EPRI participates in the formulation of the HRP experimental program through formal membership in the Halden Program Group, which oversees HRP program planning activities. E. L. Zebroski, Director of EPRI's Nuclear

THREE-PIN-DIAMETER RIG



Systems and Materials Department, is currently chairman. Milton Levenson, director of EPRI's Nuclear Power Division, is the EPRI representative on the HRP Board of Directors.

In addition, under its charter as a member of HRP, EPRI has become actively involved as a direct experimenter through sponsorship of complex experimental rigs for studying the effects that changes in axial power shape during power operations can induce in the pellet-cladding interaction (PCI) phenomenon, which can degrade the performance level of a fuel rod by reducing effective rod lifetime.

Economic significance

Today's LWRs operate under a variety of restrictions (imposed by the utility, the reactor, or the fuel manufacturer) on the rates at which the power production level can be altered because of variations in the required output loading demands or the necessary shutdown-startup cycles. These restrictions, primarily on the rate of power rise, detract directly from nuclear plant operating capacity factor, (which is, essentially, the ratio of power *actually* produced to power that *would be* produced if the plant ran at full power 24 hours a day, 365 days a year). They are the result of a conservative approach to avoid inducing excessive PCI. Fuel rod damage that may be caused by exceeding these restrictions or by following restrictions that are not sufficiently qualified can further reduce capacity factor and plant availability by shortening rod lifetime.

In addition to the above restrictions, NRC may impose licensing restrictions on peak operating powers. These limitations are usually related to safety considerations but may be directly related to fuel rod performance, as occurred in 1973 when several power reactors were temporarily derated pending study of fuel pellet densification (a problem since corrected).

It has been estimated that the total effect on capacity factor of these restrictions and the number and length of refueling outages is equivalent to a loss in capacity factor of 4–6%. Such a loss in capacity is a direct loss in total U.S. electric generating capability. To express this in terms of money: Calculations show that a 1% increase in plant capacity factor for one 1000-MW nuclear plant (which can serve the needs of a city of one million) will save the parent utility $1–$2 million each year in the cost of purchasing alternative fuel (oil). Thus, the U.S. as a whole in 1985 alone could save about $300 million (at 1977 oil prices) for a 1% improvement in capacity factor. Hence the 4–6% loss in plant capacity factor attributable to reduced fuel rod reliability is worth $4–$12 million per year for each reactor now operating.

This is the great incentive for work on improving fuel rod reliability. The detailed study of fuel rod behavior, such as EPRI is doing in test reactors at Halden and Studsvik, supplemented by the less detailed but more numerous behavioral studies in U.S. power reactors, provide the basic building blocks of the understanding necessary to improve this reliability.

EPRI's experimental rigs

The EPRI-sponsored experimental program at Halden used a rig design similar to that described above, but with the important additional capability of being able to maneuver the rod power levels axially on a regional basis, as well as doing so simultaneously over the entire length of the fueled region. Thus it could closely simulate the effect that control rod movements during power operation can have on the axial power shape.

In summary, the following specific features are incorporated in EPRI's two Halden experimental rigs (IFA-435 and IFA-512):

- Each rig can contain three BWR-type fuel rods.
- Four axially segmented coils containing helium-3 (a neutron absorber) surround the rods, providing the capability of localized and independently controlled

changes in axial power shape and magnitude by changes in helium pressure in each of the coils.

- Fuel rod dimensional changes are monitored by cladding profilometers that can measure rod diameter at one azimuthal location and axially over the fueled length of each rod and by rod length extensometers. Both systems provide real-time data during reactor power operation.

- Rig heat balance is monitored by neutron detectors (one of which travels with the profilometer), coolant flowmeters, and thermocouples.

- The design of the rigs allows for removal and replacement of rods during reactor shutdown (i.e., the rig design permits reuse).

Operations and achievements

Operation of EPRI's IFA-435 rig started in December 1975 and ended prematurely in October 1976 because of instrumentation failures. Data from the rig was intended to provide high-quality characterization of the evolution of the mechanical conditions (e.g. fuel rod diameter and length changes) resulting from a controlled power-time cycle. The objective was to combine such data with detailed pretest fuel rod characterization and posttest nondestructive and destructive examinations to give a comprehensive data base for use in investigating the local effects on fuel rods caused by control rod movements at power.

The IFA-435 rig was successful from the standpoint of proof of principle, despite the premature end of its service life. It demonstrated excellent operational characteristics, both in regional power control and in measurement capability.

An important result of its operation is that the three test rods, which for the most part had modern BWR-type diametral gaps between fuel and cladding (or smaller), survived five large-magnitude, relatively rapid power increases with apparently only elastic diametral pellet clad mechanical interaction. These tests were at low burnup—about 3000 MWd/t.

Because of IFA-435's instrumentation failure, a second and nearly identical rig, IFA-512, is being fabricated for insertion into the Halden reactor in August 1977. The new rig incorporated refinements in both instrumentation and general design, based on experience gained with IFA-435 and other rigs.

The general experimental objectives for IFA-512 will remain the same as those for its predecessor, including incorporation of preirradiated fuel rods into the rig for first-time power ramping at medium burnup levels (5000–10,000 MWd/t).

Computer control work

Parallel with the studies of fuel rod performance, HRP has extensively investigated computerized tracking and control of reactor operation. The OPCOM (operator-process communication) system has been one of the major products of this work. This system consists of computer-controlled color television displays, combined with a desk-size control console, to provide both an information exchange between the operator and a process and a direct operator control of the process.

As applied at Halden, OPCOM is a complete secondary control system (still only desk-sized) that can impose total operational control on all HBWR systems, from direct control of reactor power through final disposition of the end-product steam supplied to the Saugbrugs paper mill.

At a simulated level, variations of OPCOM have been used to manage core power in large commercial-scale reactors. Additionally, current studies are extending the concept to real-time fault-tree analyses of perturbed reactor systems that not only provide the operator with predictions of expected events if left uncorrected but also with recommended control steps for correcting the perturbed conditions.

EPRI and HRP in perspective

In addition to its active experimental participation, EPRI also maintains close follow-up of HRP and selected experiments by other sponsoring participants. This entails active participation in planning the base program experiments and guiding data analysis activities.

Starting in 1977, under EPRI management, the HRP has increased efforts to translate the results of the base program experiments into qualified data packages. These can be used quantitatively in the verification of fuel performance models aimed at more reliable predictions of dimensional behavior of power reactor fuels. As such, the data packages will be actively incorporated into the data base for an EPRI project on fuel rod mechanical performance monitoring (RP971).

To facilitate implementation of this experimental program, two EPRI staff members are now stationed at Halden: David Franklin, with the fuel testing program, and Mike Miller (on loan from Pacific Gas and Electric Co.), with reactor control and instrumentation.

HRP has contributed greatly to our understanding of the basic effects that produce fuel distortions and eventually failures. Experiments have addressed both the mechanical and the chemical (stress-corrosion cracking) aspects of the PCI failure processes. In the former category, it has been shown by pioneering in-core diametral measurements that the uranium oxide fuel pellets can force the cladding to expand and deform permanently in the early stages of irradiation. Subsequently, the cladding and pellet stack appear to adjust to each other and no further deformation occurs, unless the irradiation conditions are changed (e.g., maximum power increased). This adjustment phenomenon is called fuel conditioning. The PCI behavior of fuel rods is a major factor in shaping manufacturers' operating recommendations to the utilities. Controlled modification of the rod PCI behavior to permit a wider spectrum of operational choices and to attain a consistently long, effective lifetime (a more compliant system) is the main thrust of the EPRI Fuel Performance Program, and we anticipate that our involvement in HRP will help greatly in achieving this goal.

Energy Conservation: Behavioral Considerations

by Robert Crow

When individuals and society are faced with energy-conserving policies and technologies, how do they respond? EPRI uses data about economic variables, technological change and performance, and market restrictions to assess the conservation issue realistically.

□ An EPRI program article

Government slogans and higher prices aren't going to force me to give up what I need.

Robert Crow is the manager of the Energy Demand and Conservation Program in the Energy Analysis and Environment Division, EPRI.

Energy conservation has become virtually everyone's objective. A number of technological and social means have been advanced to reach the objective, but the means themselves have seldom been carefully investigated as to their feasibility or their more far-reaching societal and economic impacts. This lack of evaluation presents an obvious problem. Energy conservation is vital to the nation's energy future, and the degree of its success will significantly influence technological changes and the increased capacity in energy production, transmission, and distribution that will be needed.

Relatively little research has been done to assess the public's acceptance of energy-consuming technologies. Most research has been expressed strictly in terms of financial and engineering considerations. Little has been done to determine the way in which people react to cost differentials and to various characteristics of service provided by the different energy-related technologies. A great deal more needs to be learned about how energy costs influence the rate of technological change and how they influence the use of given stocks of energy-using equipment. Such behavioral factors are considered in the research being carried out by EPRI's Energy Demand and Conservation Program.

Defining the terms

Webster's New Collegiate Dictionary defines *conservation* as "a careful preservation and protection of something, especially the planned management of a natural resource to prevent exploitation, destruction, or neglect." In applying this definition to energy, the key is "exploitation"—usage that is in some sense excessive. Thus, in talking of energy demand and conservation it must be clear that these are not two separate topics; conservation is one aspect of the more general problem of energy demand or use. (An EPRI program title of "Energy Demand, *Including* Conservation" would make greater sense semantically.)

Implied in the definition of conservation is action that would not be undertaken by individuals or groups motivated solely by self-interest. Conservation is either an altruistic act by individuals or a social act in the form of public policy, where it is perceived that society's well-being is not necessarily the well-being of self-interested individuals.

Also associated with conservation is action arising from a revised perception of self-interest due to price changes ("Since energy costs more now, I will use less"); and changes in tastes ("I find I actually sleep better with the thermostat turned down than I did when I kept it at 72 degrees all night").

Changes in values and public policy

Altruistic energy conservation and changes in tastes are both concerned with changes in the values of individuals rather than with changes in the external environment to which individuals respond. The distinction between them is that altruism requires forbearance and a concept of ethical behavior ("I would like to and can afford to air condition my house to 70 degrees, but it would be socially irresponsible to do so"). Simple changes in tastes, however, have no ethical content; they simply reflect the fact that people now like some things more and others less.

In practice, it is very difficult to disentangle these motivations. What may originally have been an act of altruism might evolve to a set of preferences that would endure regardless of the original motivation. It is even more difficult to determine the *extent* of such changes in values. Certainly there is no overwhelming evidence that a conservation ethic has materialized for the population as a whole. However, it is possible that such a change in values could be carried forward by people in their twenties who are just now entering the labor force and starting families. This would suggest that such changes in values are evolutionary, rather than immediate, but potentially significant nonetheless.

Another question concerning values is whether they change systematically over an individual's life cycle. If they do, then the apparent demographic shifts in the United States toward a generally older society may have important energy conservation implications.

It is important to keep in mind that questions of changes in values are not limited to the residential sector. Changes in values in terms of social responsibility in the industrial and commercial sectors may also play a significant role in energy conservation.

Public policy, in the form of moral persuasion, may also influence changing tastes and stimulate altruistic motives. Usually, however, public policy manifests itself through more direct methods by the creation and adoption of standards—such as the 55-mph speed limit and ASHRAE 90-75 for the construction of new buildings; by rationing, such as FPC control of gas supplies, the FEA gasoline allocation program, or a World War II-style coupon program; or by influencing the market through a tax on the use of a scarce resource or by a subsidy to promote more efficient use. There may also be combinations of policy tools. An excise tax on sales of automobiles that get less than 25 miles per gallon of gas is an example of the combination of a standard and a tax.

Role of the marketplace

Conservation also takes place through the natural interplay of market forces. In all societies—rich or poor, socialist or capitalist, primitive or advanced—as a given resource becomes more scarce, a greater amount of other resources must be given up in order to obtain it. Or, more simply, the less there is of something, the higher its price. Since higher energy prices mean that a greater amount of one's

We're using too much too fast, when we really need to save for the future.

income or wealth must be given up to obtain energy, there is a natural tendency on the part of households and firms to use it more carefully, or limit its use.

In relation to energy, market forces operate through two mechanisms. The first is the reduced utilization of energy-using equipment of a given type—such as turning off lighting and machinery when not needed, waiting until there is a full load to wash dishes or clothes, turning down thermostats in winter or turning them up in summer. The second market mechanism is that an increase in energy prices induces users to purchase equipment that is more energy-efficient or that uses less expensive forms of energy. It becomes clear to manufacturers of energy-using equipment that potential customers will be taking energy consumption into account in purchasing decisions. Thus, there is an incentive (through technological innovation) to develop more efficient equipment or manufacturing methods, such as more energy-efficient ways of producing industrial process heat and of improving the efficiency of appliances. Also, there are new ways of accomplishing old objectives, such as heating and cooling with heat pumps in conjunction with solar heating. Finally, market forces create an incentive to invest in methods that make existing capital more energy-efficient, such as increased insulation and installation of heat recovery devices.

Market forces involving the use of any type of durable equipment—and durable equipment is always involved in the use of energy—take a long time to work themselves out. The costs of replacing less energy-efficient capital equipment with more energy-efficient capital equipment are likely to be so high that they overwhelm the savings to be realized in energy conservation. Thus, conservation effects from technological change occur only as equipment is replaced in the normal cycle of business and household activity, with relatively minor (at present, at least) accelerating tendencies resulting from high energy prices or unavailability of sources. This implies that in looking at the effects on energy consumption represented by such measures as long-term price and income elasticities, the fact that these are *long-term* effects should be kept clearly in mind.

Finally, there are interactions among all the motivating factors for energy consumption, particularly between public policy and market forces. Standards, rationing, persuasion, taxes, and subsidies aimed at energy conservation would all be expected to result in the initiation and acceptance of new technologies oriented to using energy more efficiently and to modifying energy consumption behavior with a given stock of equipment.

What are we really conserving?

A somewhat separate, but critical, aspect of energy conservation is the careful identification of what is being conserved. Energy per se is not especially scarce or valuable. What is scarce is a supply of energy resources that can be converted with reasonable ease to human purposes. While it may be true that "a rose is a rose is a rose," a Btu (of coal) is not a Btu (of petroleum) is not a Btu (of natural gas). Those resources that are easily used, have multiple purposes, and have low reserves or high extraction costs will be expensive. This, in a nutshell, is the "energy crisis." Petroleum and natural gas satisfy all the above criteria for costliness, with the added complication that supplies often respond to political rather than economic forces.

The implication of differential characteristics of fuels is that energy conservation is often, more precisely, "interfuel substitution." Electricity, of course, uses coal and uranium—fuels that do not meet all the criteria that make prices high or cause administrative restrictions on supply. Thus, one result of conserving petroleum and natural gas may be to increase the consumption of electricity as gas and petroleum users switch. This results in an apparent paradox—a relatively "inefficient" conversion of energy (from fuel to electricity) could substitute for an "efficient" one (direct combustion).

This has been the cause of a great deal of confusion on the part of those adhering to a strict Btu interpretation of energy conservation.

The paradox is resolved by separating thermal efficiency (in which one Btu is as good as another) from economic efficiency (in which the scarcity of the energy source and the usability of the Btu are of paramount importance). The implication, of course, is that meaningful energy conservation (in the sense of conserving the scarcest, most usable fuels) could actually

Our company had to put tight limits on energy use because of new government restrictions.

result in more Btu's being consumed by the process of "inefficiently" converting abundant, otherwise unusable energy sources. Solar energy conversion is a prime example.

EPRI's role

In order to understand EPRI's research efforts, it is vital to realize that EPRI itself does not design or foster any type of public policy. This position is necessary in order to maintain credibility and acceptability of research sponsored by an institute created by an energy industry. One facet of EPRI's research is focused on the development of energy-conserving end-use technology (in the Energy Utilization and Conservation Technology Program of the Fossil Fuel and Advanced Systems Division). Another facet of conservation-related research is limited to a passive role of understanding conservation behavior and assessing the impact on energy demand of conservation-oriented technology and policy, as well as market forces (in the Energy Demand and Conservation [ED&C] Program of the Energy Analysis and Environment Division). Two important focuses of EPRI's research in this area of energy conservation, then, are behavioral research studies and analysis of economic factors.

The role of behavioral research in energy conservation is to assess the extent to which policy proposals and technological options reach their desired objectives or are accepted by the marketplace. Thus, conservation is inherently one aspect of the more general problem of energy demand or usage behavior and is inextricably woven into ED&C's more general demand or consumption studies. This orientation is reflected in ED&C's overall effort to forecast energy consumption, and therefore conservation, under alternative sets of assumptions about economic variables, technological change, and restrictions on supply.

The research areas in which ED&C projects are underway are the residential, industrial, commercial, and transportation sectors, as well as time-of-day, seasonal, and regional studies. The types

It's getting expensive, and I'm cutting down to cut my costs.

of research under way are:

- Aggregate time series analysis
- Assessment of energy-conserving technological change
- Microlevel behavioral studies
- Technical performance and measurement studies

Analyzing economic influences

Economic variables affecting energy consumption are those related to levels of income or economic activity, to prices of electricity and other forms of energy, and (in the case of manufacturing and agriculture) to prices of other factors of production. Of these variables, relative prices have the primary influence on conservation and interfuel substitution. Higher electricity prices relative to prices of other forms of energy and other factors of production would imply a decline in use, due to an inducement to increase efficiency and to switch to other energy forms. Increases in income or output would have the effect of increasing energy consumption in general.

One way of conducting studies on these general economic issues is through the analysis of aggregate data (data on state or national consumption over time). Such data are generally on global figures, such as total kWh for a given sector or system peak demand. Also, they may be on detailed aspects, such as a breakdown between stocks of energy-using equipment and their rates of utilization.

An example of an aggregative study used currently in EPRI's internal forecasting efforts is *The Residential Demand for Energy* (EPRI EA-235). This study investigates energy use and appliance purchases, with special attention to the effects of the electricity rate structure, weather effects, and personal income.

In addition, studies are conducted on microlevel data (data on individual households and firms). Samples of such data allow analysis to be much closer to the theory of household behavior and the theory of the firm and permit analysis of factors obscured by aggregation and factors that change slowly over time, such as shifts in demographic composition.

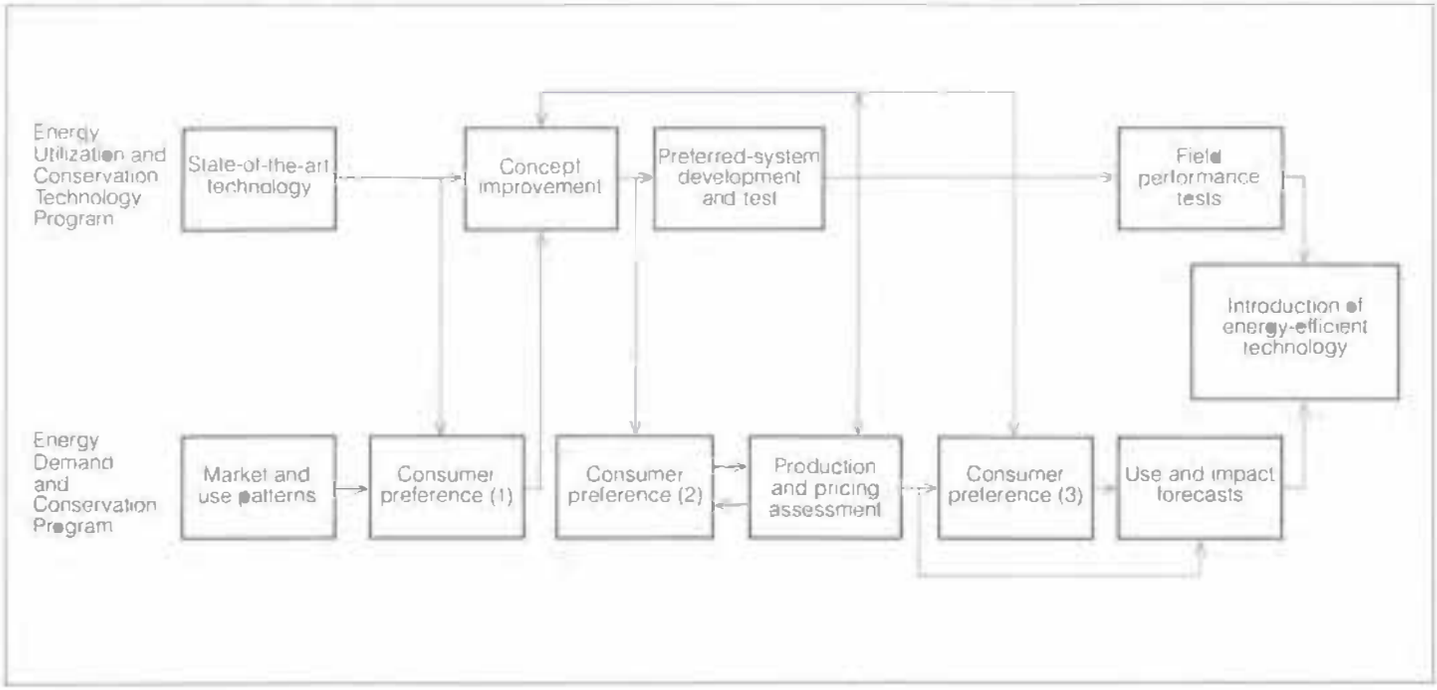
Assessing impacts of technological change

As stated earlier, energy-conserving technological change will be induced by changes in energy prices and supply restrictions. Change may also occur autonomously for reasons largely unrelated to energy conservation, as in the case of transistors replacing vacuum tubes.

The implications of both induced and autonomous technological changes are incorporated in ED&C's consumption forecasts. Since the development of a new energy-conserving technology is not necessarily followed by its adoption and use, a major aspect of the program's research is oriented toward answering a sequence of questions:

- *How well do existing and prospective energy using technologies satisfy users' needs?* What are the capital costs, the energy-using characteristics, and other relevant factors (such as reliability and ease of operation) that will influence acceptability to energy users? In the case of the electric automobile, for example, such factors would include the vehicle's range, rates of accel-

Figure 1 This cycle of interaction between EPRI's research programs indicates how state-of-the-art technology, economics, and consumer preferences are integrated in the development of advanced, energy-efficient technology.



eration from a standing stop and at passing speeds, and internal space.

▫ *What are the prospects of supplying the new technology on a sufficient scale and at a low enough price for it to be adopted?* Assessment of the market potential for new technologies and of the capability of their being supplied at various prices makes it possible to determine how much capacity is needed.

▫ *What are the implications of the technologies for electric utility system loads?* Information on seasonal and time-of-day loads, as well as on annual kWh sales, is required.

One investigation of the above issues is a study on the impact of electric passenger automobiles on utility system loads, 1985–2000 (RP758).

Were values concerning energy consumption to change, they would have an impact separate from either economic factors (income or price) or technological innovation. Our working hypothesis has been that such changes are less important than the influences of income, price, and technology, and we have largely ignored them to date. However, we recognize that this hypothesis should be examined carefully, and the importance of changing values will receive increased attention in future ED&C research.

Technical performance and measurement studies

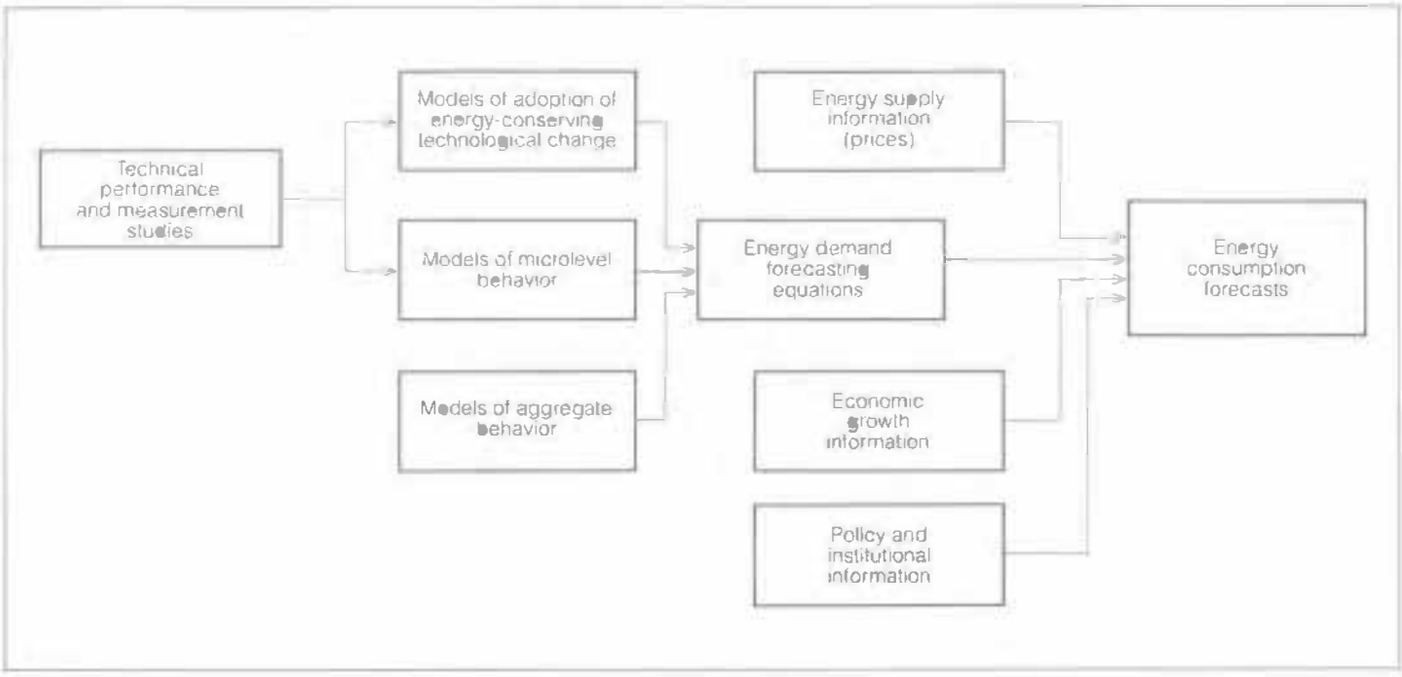
In many cases, basic information is lacking on energy consumption behavior and on the performance of energy-consuming technology. Thus, ED&C engages in fundamental data development that encompasses surveys and group load research and in engineering analyses of technical performance. This survey research provides direct input to behavioral studies of energy consumption. Also, it is coupled with studies of the acceptability and impact of particular technologies, such as residential heat pumps.

A major effort in this type of analysis is to determine the differences between theoretical or design efficiencies and actual operating efficiencies. Much of this work involves engineering analysis and experience with engineering measurement, as well as statistical survey design. Therefore, there is close interaction between this ED&C work and that of the efforts of the Energy Utilization and Conservation Technology Program to develop new technology (Figure 1). (For additional discussion of these program interactions, see "The Heat Pump: Renewing an Option," EPRI JOURNAL, October 1976, p. 20.)

Forecasting

The various types of energy demand research—the influences of income and prices, the influence of technological change, and the technical performance and measurement studies—are integrated in the ED&C in-house effort to produce forecasts of national energy consumption and typical utility load profiles under alternative assumptions concerning economic growth, conservation policies, and changes in energy prices and other relevant prices. The way in which this integration takes place is shown in Figure 2. Data from technical performance and measurement studies, collected on a household or establishment basis, are used in the microanalytic studies of the influence of income and prices and in the studies to assess the impact of technological change. These are combined with

Figure 2 Basic data are used to construct models of energy usage behavior, which, in turn, are combined with information on policies, prices, and economic growth to produce forecasts on energy use.



models of aggregate behavior to provide energy demand forecasting equations. These equations, in turn, are combined with price information (which may or may not contain information on energy conservation policy), with information on economic growth, and with information on nonprice policies and other institutional information regarding energy conservation. This combination of models and assumptions results in an annual set of energy consumption forecasts. Thus, what is produced is a range of possible futures rather than a single-point forecast. In the future, these forecasts will be integrated with the work of the Supply Program and the Systems Programs to produce an integrated, comprehensive forecast of energy supply and demand and their impacts on economic growth. Thus, it will be possible to obtain a comprehensive view of the role of energy conservation policy in energy consumption and national economic growth.

Market disequilibrium

A major problem in energy demand and conservation analysis is that energy markets have had, and probably will have, a serious disequilibrium between supply and demand. It is tempting to regard phenomena such as the Arab oil embargo, restrictions on interstate gas supplies, and possible future inadequate electric power capacity as short-run problems. However, not only is the long run made up of many short runs but short-run problems have long-run implications. This is currently seen most clearly in natural gas markets, where curtailments and restrictions on new connections appear to be resulting in the installation of a significant amount of electricity-using equipment where economic considerations, even with considerably higher gas prices, would normally dictate gas-using equipment. Moreover, even if these restrictions were lifted tomorrow, many industrial plants and residential and commercial buildings would continue to have electric equipment—the savings in switching back to gas being insufficient to offset the cost of replacing the equipment.

Such market disequilibrium considerations are a major concern in ED&C's forecasting efforts and are often handled on an ad hoc basis—formal analysis being incapable of handling what are essentially administrative constraints. Problems of this sort also place a premium on regional analysis, a high-priority area in the ED&C program.

Looking ahead

Energy conservation is and will be an important element in the U.S. energy future. In addition, as energy prices increase, the marketplace will encourage energy conservation through reduction in the rate of use of existing equipment and through technological change oriented toward increased efficiency. Changes in values are also likely to have some impact on energy consumption, and we can expect many policy proposals and technological innovations related to energy conservation to be advanced.

As noted earlier, behavioral research on energy conservation has been relatively neglected. In such research it is crucial to bring knowledge of energy conservation from the realm of speculation on what the effects ought to be to that of realistic assessments of the behavior of individuals and societies faced with energy-conserving policies and technologies.

At the Institute

New Insulating Material Cuts Costs by Half

A new transmission-line insulating material, which has twice the dielectric strength and half the cost of porcelain, has been successfully developed (RP480).

The new material, Polysil, is a kind of polymer concrete developed by Westinghouse Electric Corp. under an EPRI contract.

Polymer concrete as an insulating material was the subject of a March 14 and 15 workshop sponsored by EPRI and held in Palo Alto, California. The workshop allowed polymer concrete specialists to share their knowledge and to recommend techniques for field-testing Polysil. Representatives from the utilities, research institutes, government agencies, and manufacturers attended.

According to Robert Perry, director of the EPRI Transmission Department, the potential savings are significant for utilities that begin to use polymer concrete insulators. He estimates that utilities could save up to $7.5 million annually if a mere 5% of their insulators were made of polymer concrete.

Four of the participants in an EPRI workshop on polymer concretes were (from left) Leslie Smith, National Bureau of Standards; Larry Kukacka, Brookhaven National Laboratory; Robert Perry, EPRI; and Clarence Zeise, Westinghouse Electric Corp.

This lightning arrester housing model contains Polysil, a new material developed by Westinghouse Electric Corp.

Regional Meetings Focus on Electric Energy Options

Pay a little now or a lot later.

That was the message from Chauncey Starr, EPRI president, to more than 1200 utility executives and their guests who attended EPRI regional meetings in seven major U.S. cities in March.

Starr described research and development as a means of "minimizing the financial impact of the many uncertainties facing the electric utility industry for the balance of the century."

The EPRI president told his audience that the real justification for a large R&D program is its potential for holding down capital and operating costs and thereby helping to provide electricity at a reasonable cost to the consumer.

The regional meetings were held to bring utility executives up-to-date on EPRI activities, accomplishments, and future plans, as well as to generate feedback from utility management regarding EPRI policies and performance.

One-day meetings were held in Portland, Los Angeles, Dallas, Atlanta, Chicago, Columbus, and New York City.

Workshops relating to the specific activities of the four EPRI technical divisions were held in addition to presentations by Starr and the division directors.

A 22-minute, 16-mm color-sound motion picture, recently produced by EPRI, was given its first showing at the meetings. The film, entitled "Energy Realities," deals with present and future electric energy technologies. In particular, it helps clarify some misunderstandings about such future energy sources as solar and fusion.

"Energy Realities" costs $135.00, with a 10% discount for purchases of 10 prints or more. It is also available for preview from Film Counselors, Inc., 500 Fifth Avenue, New York, NY 10036.

Conservation and the Development of All Energy Sources Urged

Reducing the nation's dependence on foreign oil must be the chief objective of any U.S. energy plan, but many questions remain as to how this can be done, said EPRI President Chauncey Starr, at a March 19 conference sponsored by the National Newspaper Association.

At the Washington, D.C., conference, Starr acknowledged that oil, while increasing in cost, will probably be available worldwide in substantial quantities for many decades, although oil resources in the U.S. are currently insufficient for our needs.

"Our land areas are pockmarked with exploratory wells, and unless our offshore continental shelf reveals large new fields, we will have to import a very large fraction of our oil," he said, adding that this is a circumstance fraught with foreign policy and international economic consequences.

Starr, who, as head of EPRI, leads a national electric energy research program that will be spending more than a billion dollars over the next five years for improvements in the technology of electric utility operations, also called for a "pragmatic balance of values in all environmental decisions." He said that the recent extreme concern with environmental impacts has created a new dimension that is often in conflict with all the energy-using activities of our society. "Balancing environmental objectives with other socially desirable goals is our country's second major energy problem," he asserted.

The close relationship between economic well-being and sufficient energy supplies was also discussed by Starr. He said that because energy costs are a basic input to the total cost of all goods and services, higher energy prices create a substantial increase in all costs.

"But even more important," he noted, "is the vital need of our economy for continuity of energy supply. Thus, OPEC control of export oil prices and availability, combined with the high marginal costs of domestic fuel substitutes, results in a significant present and foreseeable economic burden on our national output of goods and services, as well as a continuing threat of economic crises."

According to Starr, the most important issue for public consideration is deciding the level of economic growth that would be acceptable to the country. "If we establish the historical growth in average income per worker and full employment of the labor force as goals, we will almost certainly need an annual energy supply about twice the present consumption by the year 2000—even with reasonable conservation by improved technology."

Starr further stated that an intense dedication to conservation by lifestyle change would reduce this need, as would a lower expectation of income growth. "And in the end," he said, "energy malnutrition may force us to make such changes."

The EPRI president concluded by urging increased efficiency of energy use through technological improvements, as well as the increased development of all domestic energy sources.

"Simple as this recipe sounds, enthusiastic public support of these steps has been lacking so far—probably because increased consumption of OPEC oil is a less demanding alternative. We all hope that better public perception of the real alternatives will move us to more effective national action."

Conference on Rate of Discount

A two-day conference in Washington, D.C., attended by many of the world's leading economists, was recently held as part of an EPRI research project to develop and publish a book on the appropriate rate of discount for energy investment and R&D decisions (WS76-91-1). Discounting is a method used to compare dollars paid and received during different time periods. It is an important part of any investment decision because such decisions generally involve comparing present cost outlays against benefits received at different times in the future.

According to EPRI Systems Program Manager Martin Greenberger, who initiated the project, there is considerable questioning of the 10% discount rate prescribed by the U.S. Office of Management and Budget as a national standard. The discount rate can be a critical parameter in the energy investment and R&D decisions currently being taken by individual companies, the industry, and the federal government. A company's decision on whether to convert to coal and the country's decision on whether to proceed with fusion development are important cases in point.

The conference, sponsored by EPRI, was organized by Professor Robert Lind of Cornell University and administered by Resources for the Future, Inc., a Washington, D.C., research organization. Papers and discussion from the conference will be revised by the participants and edited by Lind and Greenberger in a volume to be published by Resources for the Future under the tentative title, *Rate of Discount: Its Meaning and Appropriateness in Energy Investment and R&D Decision Making*. Greenberger and Lind will write additional chapters for the book on the fundamentals of the discount rate approach, prior work on the subject, new directions being pursued by contributors to the project, and the major conclusions and insights coming out of the analyses.

Nobel Prize winners Kenneth Arrow of Harvard and Tjalling Koopmans of Yale will be among the twenty or so contributors to the book. They, along with numerous other distinguished economists and policy researchers, were among the participants in the Washington conference. Representatives from Consolidated Edison Co., Commonwealth Edison Co., TVA, other utilities, government agencies, and research institutes also participated.

The appropriate rate of discount for energy investment and R&D decisions was the subject of a Washington, D.C., workshop sponsored by EPRI and Resources for the Future, Inc. In discussion are (from left) Gordon R. Corey, vice chairman, Commonwealth Edison Co.; Kenneth Arrow, professor of economics, Harvard University; Martin Greenberger, manager, EPRI Systems Program; and Robert Lind, professor of public policy and administration, Cornell University.

Project Highlights

Ground Broken for Solar Home

In April construction started on a residential solar experiment that is expected to yield the most comprehensive technical and cost information to date on solar heating and cooling systems.

In a cooperative venture with building contractors and local utilities, EPRI will evaluate nearly 100 variations of new and proven energy-conserving systems and features in 10 houses being constructed in the northeast and southwest regions of the United States. Designed and managed by Arthur D. Little, Inc., the EPRI program is the first solar heating and cooling experiment to consider the impact of residential solar systems on utility systems together with customer benefits.

John E. Cummings, acting manager of EPRI's Solar Energy Program, commented that the need for backup power during periods of cloudy weather "makes it essential that solar heating and cooling systems be designed to work with the utilities. If properly managed, solar energy systems that are compatible with conventional power supplies could realize savings for both users and utilities by reducing utility requirements for generating capacity."

Among the energy-conserving options being studied by EPRI in conjunction with solar energy are load management (a system that shifts demand for electricity to off-peak periods) and heat pumps. A heat pump is a device that can extract energy from relatively low-temperature thermal sources, such as outside air, and convert it to a higher, more usable temperature for heating homes. A variety of heat pumps will be tested in several of the experimental homes.

In addition to tighter construction, other energy conservation measures under study include improved insulation and double glazing.

On completion of the three-year program, EPRI will make the designs of the houses and solar energy systems available to the nation's electric utilities and builders. Operating data will be distributed as they are collected and analyzed.

Both traditional and contemporary architectural designs are used in the experimental houses, which will be occupied by families in early 1978. Although the experimental models are in the $60,000–$75,000 range, the data generated will be applicable to houses in all price categories.

Daniel Nathanson, manager of Arthur D. Little's Energy Systems Group, is directing the EPRI residential experiment. In designing the program, his task force team selected for comparison four general classes of heating and cooling systems that apply to all-electric, single-family residences. Conventional systems, such as electric resistance heat or heat pumps, will be evaluated separately, as well as with load management and solar energy systems, singly and in combination.

Nathanson points out that in addition to cost and reliability analyses, solar energy systems must be examined in terms of their compatibility within a specific utility service area. "Utilities are controlled by autonomous state public service commissions, and regulations vary widely from state to state."

According to Nathanson, the findings from the research project will provide utilities with the data they need to structure equitable rate schedules for their solar and nonsolar customers.

Long Island Lighting Co. and Public Service Co. of New Mexico are the utilities participating in the study. Five houses will be constructed within each of the two service areas in Wading River, Long Island, New York, and Albuquerque, New Mexico.

The builders are Clarendon Construction, Inc., Long Island, and Mossman-Gladden, Albuquerque.

Chemicals for Preserving Wood Poles

Three volatile chemicals from the agricultural industry can control internal decay in Douglas fir power poles for at least seven years, according to an interim report released recently by EPRI (*Controlling Biological Deterioration of Wood With Volatile Chemicals*, EPRI EL-366.)

The liquid fumigants, Vapam, Vorlex, and chloropicrin, will be evaluated over the next three years to determine their effectiveness in controlling decay fungi in the other tree species used for power poles, western red cedar and southern yellow pine.

The research project is being jointly funded by EPRI and Oregon State University. The Forest Research Laboratory of OSU is the contractor for the project and has been conducting research on Douglas fir poles for over 10 years. The early research was funded by Bonneville Power Administration, Northwest Public Power Association, Pacific Power & Light Co., and Portland General Electric Co. EPRI, shortly after its formation in 1973, joined this research effort.

As part of the research, investigators are developing more efficient methods for applying fumigants, as well as evaluating improved methods for detecting internal decay in wood poles.

According to Robert Tackaberry, EPRI project manager for this research, about 500,000 fir poles are replaced annually at an estimated labor and materials cost of $500 per pole. If, for example, 100,000 poles last an additional 10 years because of the new fumigant treatment, utilities could save about $9 million annually. The cost of replacing wood poles has increased steadily and was a major factor in helping to spur interest in this research.

The volatile chemicals are poured into holes in decaying Douglas fir poles and diffuse through the wood for about 8 ft above and below the groundline to eliminate decay fungi. Re-treating poles with these chemicals at intervals of seven years or longer extends the service life of poles indefinitely.

Ten utilities are cooperating with OSU in field evaluation studies. The utilities are Bonneville Power Administration; Commonwealth Edison Co.; Consumers Power Co., Inc.; The Detroit Edison Co.; Forest Grove Light & Power Dept.; Georgia Power Co.; Pacific Power & Light Co.; Portland General Electric Co.; Salem Electric Cooperative; and Virginia Electric and Power Co.

A research project, jointly funded by EPRI and Oregon State University, has found chemicals to control internal decay in certain types of wood power poles. As part of the project, an OSU researcher drills a hole for insertion of the chemical fumigants.

Automating Distribution Systems

The signing of four contracts for a $7 million project to test the feasibility of using two-way communication systems for automating electrical distribution systems was announced in April by EPRI and ERDA.

The two-year effort is also geared to helping utilities in load management, which is the attempt to even out the peaks and valleys of electricity demand.

The research objective is to evaluate the capability of communication and control systems to accurately record, transmit, and receive billing and control information. If successful, two-way communication systems will allow utilities to set different rate structures, for example, three different time-of-day rates.

As part of the project, four manufacturers will install a communication system on the facilities of its host utility. The four manufacturer-utility teams are Westinghouse Electric Co. and Detroit Edison Co.; Compuguard and Carolina Power & Light Co.; American Science and Engineering and San Diego Gas & Electric Co.; and Darco Corp. and Omaha Public Power District.

"Each of the four systems being tested will automatically record data daily at the customer's meter for three time periods," explains William E. Blair, EPRI project manager in the Electrical Systems Division. According to Blair, the data will then be transmitted to a central location and stored in a computer.

"Eventually, this data can be used by the utility to set a rate schedule that gives the customer an opportunity to save money by using energy at off-peak periods," says Blair, who is in charge of this project for EPRI.

During certain hours of the day, the demand for electricity is very high, while at other times, demand is very low. Utilities are obligated, however, to have sufficient generating capacity to meet peak periods of electricity demand—even though full capacity is rarely needed. To reduce peak demand and to use system equipment more effectively, electric water heaters and air conditioners, for example, could be turned off for brief periods during peak times of power de-

mand. According to Blair, experience has shown that customers are not ordinarily inconvenienced by such controls.

"In the long run," says Blair, "these two-way communication systems should provide sufficient energy savings to help offset rising electric, gas, and water bills." According to the EPRI project manager, such savings would occur because the systems would improve the efficiency, operation, and reliability of utility service.

Blair cautions, however, that utilities "cannot be expected to buy this communications equipment unless it is cost-effective. It must be available for about $100 per customer in today's dollars to be attractive to the utilities."

Each of the systems being tested will monitor a minimum of 700 locations, including at least 650 customer meters. The meters can be read faster than one per second, so all meters in each trial system can be read in less than 15 minutes. The units will also be designed to make meter-tampering extremely difficult.

In addition, each system will have the capability of switching capacitor banks, sectionalizing feeders, and aiding in locating faults. The systems will also demonstrate the capability of monitoring equipment parameters, such as transformer temperatures.

The systems will be tested in a wide range of industrial, commercial, and residential service locations. The locations have been chosen to include customers served by underground and overhead lines in urban, suburban, and rural areas. In the industrial areas, the systems will monitor three-phase and single-phase kilowatt demand as well as kilowatt-hours.

Generally, utilities have used only one-way systems for switching loads and controlling distribution equipment. Jeffrey A. Serfass, project manager in the ERDA Electric Energy Systems Division, however, states that if time-of-day metering "merits implementation by utilities, then combining the meter reading of these more complex devices with other load management strategies warrants the use of two-way communication systems."

According to Serfass, the advantage of a two-way system is that the utility can not only transmit commands but also receive data on the distribution system.

Serfass says that once the project is completed and the four communication systems are evaluated, a utility may confidently choose the best system for its particular requirements. "Ultimately," he says, "many utilities may choose a hybrid system involving combinations of power line carrier, telephone, and radio to meet their particular needs."

Reducing NO_x Emissions

New methods for reducing the emission of nitrogen oxides (NO_x) into the air from coal-burning power plants will be explored during a $2 million project announced recently by EPRI.

EPRI has awarded $1.6 million to Babcock & Wilcox Co. in Alliance, Ohio, to conduct the two-year project that will seek to develop a cost-effective technology for controlling NO_x emissions (RP899). Babcock & Wilcox, an international power generation equipment manufacturer, will provide the remaining funds.

"The federal government currently requires control of three emissions from coal-fired power plants," explained Don Teixeira, project manager in EPRI's Air Quality Control Program. "These are sulfur oxides, particulates, and nitrogen oxides. Technology is well into the commercial development phase for sulfur oxides and particulates. However, technology to provide for NO_x emission control is still in its earliest stages of development."

Teixeira explained that nitrogen oxides can be formed in two ways. The first occurs when nitrogen in the air combines with oxygen at high temperatures when any fossil fuel is burned. The second occurs when organic nitrogen present in fuel reacts with oxygen during the combustion process. The current investigation is aimed at developing techniques that will minimize the conversion of this organic nitrogen in coal into NO_x.

"This is clearly the most cost-effective approach for NO_x control," Teixeira said. "Other approaches involve complex systems, which are not only expensive but frequently convert an air pollution problem into a solid waste or water pollution problem."

Uranium Resource Study

Evaluating information on uranium resources in the United States is the subject of a new study under way at EPRI.

As part of the study, the results of ERDA's National Uranium Resources Evaluation (NURE) program and the U.S. Geological Survey's uranium research program are being examined, as well as new concepts in uranium exploration and mineralization.

The results of the EPRI study will facilitate uranium exploration and assist the electric power industry in understanding data on uranium resources, according to Jeremy Platt of EPRI's Energy Analysis and Environment Division.

The study, which will be carried out by Dames & Moore, engineering, environmental, and economic consultants, will entail a comprehensive review of over 3000 private and federal reports related to uranium resource evaluation (RP870).

The final results of the study should be available by November 1978.

EPRI Negotiates 54 Contracts

Number	Title	Duration	Funding ($000)	Contractor / EPRI Project Manager
Fossil Fuel and Advanced Systems Division				
RP358-2	U-Gas Process	5 months	6.4	Ray Zahradnik Consulting, Inc. *S. B. Alpert*
RP359-2	Autoignition Limitations of Premixed Lean Combustors	16 months	262.5	Solar Division, International Harvester Co. *D. Teixeira*
RP373-2	Utilization of Agricultural Waste Water for Power Plant Cooling	4 months	15.0	Kaiser Engineers *R. Jorden*
RP468-2	Evaluation of Electrode Materials for Slagging MHD Generator	15 months	65.0	Lockheed Missiles & Space Co., Inc. *P. Zygielbaum*
RP636-2	High-Strength, High-Toughness, Austenitic Alloys for Generator Retaining Rings	3 years	180.0	University of California at Berkeley *R. Jaffee*
RP714-3	Hydrogen Production from Liquefaction Residues	6 months	300.0	Texaco, Inc. *R. Wolk*
RP726-2	Electrolyte Development for High-Temperature Sodium Batteries	18 months	210.0	Laboratoires de Marcoussis, France *J. Birk*
RP738-1	Performance Testing and Model Development for a Wet/Dry Cooling Tower	7 months	54.0	Southern California Edison Co. *J. Maulbetsch*
RP779-9	Development of Improved Technique for Solidification of SRC	1 year	115.4	E. I. duPont de Nemours & Co., Inc. *N. Stewart*
RP779-10	Processing Coal-derived Liquids by KVB Process	3 months	5.0	KVB, Inc. *H. Lebowitz*
RP779-12	Study of Deactivation of Methanol Synthesis Catalysts	9 months	29.9	Lehigh University *H. Lebowitz*
RP790-2	Assessment of Thermophotovoltaic Conversion Using Silicon Photovoltaic Cells	13 months	90.0	Stanford University *E. DeMeo*
RP839-1	Behavior of Fine Particles in a Fluidized Bed of Coarse Material	2 years	90.0	University of Bradford, England *T. Lund*
RP899-1	Low NO_x Emission Coal Combustor Development	23 months	1,604.8	Babcock & Wilcox Co. *D. Teixeira*
RP915-1	Liquefaction Data Correlation and Analysis	17 months	227.5	The Lummus Co. *H. Lebowitz*
RP920-1	Validation of the Data Base for Fusion Reactors	6 months	97.0	Science Applications, Inc. *F. R. Scott*
RP921-1	Background Study of Linus Systems for Transmuting Fission Reactor Wastes	1 year	225.0	General Atomic Co. *N. Amherd*
RP980-1	Coal Preparation Using Magnetic Separation	5 months	46.9	Inex Resources, Inc. *S. Venkatesan*
RP980-2	Coal Preparation Using Magnetic Separation	5 months	59.9	Magnetic Corp. of America *S. Venkatesan*
RP982-4	Nitrogen Oxides Stack Emission Measurements	2 months	13.4	KVB, Inc. *M. McElroy*
RP984-1	Vibration Analysis on Rotating Auxiliary Machinery	1 year	55.0	Kenneth Medearis Associates *D. Anson*
Nuclear Power Division				
RP311-4	Steam Generator Corrosion Studies	8 months	25.0	Centre Belge d'Etude de la Corrosion *T. Passell*
RP355-9	For the Performance of Work Related to Halden Fuel Performance Data Analysis and Qualification	1 year	50.0	Institutt for Atomenergi *A. Roberts, G. Thomas*
RP501-3	Human Factors Review of Nuclear Power Plant Control Board Design Approaches	16 months	156.5	Lockheed Missiles & Space Co., Inc. *R. Pack*
RP613-2	Benchmark Analysis for Transuranics at 10nCi/g Level	3 months	12.2	Babcock & Wilcox Co. *M. Lapides*
RP822-3	A Program to Develop a Portable Radiographic System for In-Service and Repair Inspections	9 months	2.0	Philadelphia Electric Co. *E. Reinhart*
RP825-2	Radiation Control in the Primary Coolant Loop of PWR Plants	42 months	644.0	Westinghouse Electric Corp. *B. Shaw*
RP829-5	Examination of Asea Oskarshamn-1 Fuel	4 months	no cost	Asea-Atom Co. *J. T. A. Roberts*

Number	Title	Duration	Funding ($000)	Contractor / EPRI Project Manager
RP884-1	Assessment of Analysis and Measurement Techniques for Predicting BWR Control Rod Reactivity Inserting Rate	22 months	121.6	Science Applications, Inc. *J. Naser*
RP890-1	Assessment of Class 1E Equipment Aging and Qualification Techniques	14 months	149.0	The Franklin Institute *D. Cain*
RP892-4	Impact Study of In-Service Inspection Requirements on the Nuclear Industry	3 months	6.0	General Physics Corp. *G. Reinhart*
RP893-1	Evaluation and Test of Improved Fire-resistant Fluid Lubricants for Water Reactor Coolant Pump Motors	2 years	592.1	Westinghouse Electric Corp. *R. Swanson*
RP894-2	Limiting Factor Analysis of High-Availability Nuclear Plants	14 months	348.0	Combustion Engineering, Inc. *R. Swanson*
RP897-1	A Self-actuated Shutdown System for a Commercial Size LMFBR	9 months	151.2	Combustion Engineering, Inc. *B. Sehgal*
RP958-1	Development of Models for Reactor Transient Effects	2 years	498.1	Energy Incorporated *L. Agee*
RP963-2	Multidimensional Steam Generator Modeling	3 months	25.0	Cham of North America, Inc. *J. Sursock*
RP964-1	Fluid-Structure Interaction Caused by Seismic Events	11 months	89.6	Science Applications, Inc. *J. Carey*
RP965-1	Analysis of LOCA-induced Fluid-Structure Interaction	4 months	31.8	Jaycor *J. Carey*
RP970-1	Determine Electrical and Mechanical On-Line Instrumentation Monitoring Needs for Generators	3 months	278.3	Westinghouse Electric Corp. *R. Pack*
RP972-1	Monte Carlo Analysis for Validating Fuel Management Codes	16 months	97.4	Mathematical Applications Group, Inc. *F. Rahn*
RP973-1	Computer Analysis of Quad Cities Reactor Irradiation	1 year	94.7	Nuclear Associates International, Inc. *R. Whitesel*
RP976-1	Extension of ARMP for Fuel Management Applications	1 year	75.0	Nuclear Associates International, Inc. *B. Zolotar*

Electrical Systems Division

RP246-2	Fundamental Investigation of Arc Interruption in Gas Flow	2 years	372.0	General Electric Co. *N. Hingorani*
RP993-1	ARC Fault Current Limiter	2 years	165.0	University at Buffalo Foundation, Inc. *R. Kennon*
RP994-1	Passive Hot Spot Detector for Transformers	2 years	243.3	Westinghouse Electric Corp. *S. L. Nilsson*
RP998-1	Hot Stick Power Factor Meter	6 months	41.4	Electro Energy Corp. *W. Blair*

Energy Analysis and Environment Division

RP852-1	Human Response to Low-Level Noise	17 months	142.2	Bolt Beranek & Newman, Inc. *J. McCarroll*
RP942-1	Forecasting In-Plant Generation in the Industrial Sector	20 months	200.0	Mathtech, Inc. *L. Williams*
RP954-1	Initiation of Supply, Demand, and Environmental Integration	7 months	43.8	University of Texas at Austin *J. J. Karaganis*
RP1004-1	Material Damage Costs from Sulfur Oxides	1 year	81.7	The Research Corporation of New England *R. E. Wyzga*
RP1005-1	Analysis of Household Appliance Choice	9 months	40.0	Charles River Associates, Inc. *J. Boyd*
RP1011-1	Incorporation of New Technologies in Supply Estimates	1 year	70.0	J. Daniel Khazzoom *J. Searls*
RP1015-1	Model Verification and Assessment Project	3 months	95.0	National Bureau of Economic Research *R. Richels*
RP1016-1	Methods for Combining Energy Methods	2 years	116.0	Stanford University *R. Michelson*

R&D Status Report
ENERGY ANALYSIS AND ENVIRONMENT DIVISION

René Malès, Director

ENERGY USE IN ELECTRIC VEHICLES

Wharton Econometric Forecasting Associates (WEFA) is completing a study on analysis and forecasts of energy use for transportation services (RP757) and Mathtech, Inc., is finishing one on the impact of battery-operated electric vehicles on utility system loads, 1985–2000 (RP758).

The WEFA project is concerned with forecasting the quantities of all types of energy used in U.S. transportation services. Their forecasting model is broken down into urban and intercity transportation and into personal and freight transportation. The model, which analyzes the demands for transportation on each mode separately, will serve two important purposes at EPRI. First, it will provide improved forecasting equations for energy use in U.S. transportation. The transportation model will join similar energy forecasting models for the residential, industrial, commercial, and agricultural sectors and will provide EPRI with a firmer basis for in-house forecasts of U.S. energy use. Besides its forecasting application, this model furnishes a framework within which new transportation technologies can be analyzed.

An example of how the model is used in this context is illustrated in Volume 1 of Mathtech's final report on electric vehicles, to be published soon. The demand side of Mathtech's model of the electric vehicle market is linked to the WEFA demand equations for automobiles by size and type. Thus, the total market penetration by electric vehicles as projected by Mathtech is consistent with the demand projections for all automobiles included in WEFA's model.

Mathtech's analysis of the impact of electric vehicles on utility system loads is derived from a complete supply and demand model for electric vehicles. The cost or supply function for electric vehicles is derived from cost-estimating equations for each engineering subsystem within the vehicle. For instance, the cost of a battery is a function of its chief technical characteristics, such as its energy capacity. The study looked in detail at four types of batteries spanning various technologies—from the state-of-the-art advanced lead-acid battery through lithium-chlorine batteries, which may reach commercialization before the turn of the century. The demand for electric vehicles is modeled with a logit equation that relates the probability of purchasing an electric vehicle to its price and performance characteristics. The electric vehicle model of energy use has different driving-cycle options for urban, suburban, and commercial use of the vehicle. The commercial driving cycle is characteristic of the driving cycle of the U.S. electric postal delivery van.

Preliminary calculations with Mathtech's model show that the impact of electric vehicles on time-of-day load patterns may not be a significant load component before the year 2000. These early results should be treated with caution by utility planners. They are based on relatively optimistic assumptions about the increased fuel efficiency in gasoline-powered automobiles, no more stringent air pollution regulations than are currently in force, no government subsidies for the production of electric vehicles, and an unsophisticated demand model. In the work reported in Volume 1, Mathtech concentrated on developing reliable models of electric vehicle costs and energy use, while devoting

Electric Vehicle Council

Preliminary conclusions of an EPRI-sponsored study predict that electric vehicles are not likely to add significantly to utility system loads before the year 2000. Utility planners are cautioned, however, that this forecast is tentative, pending further study. More than 100 Battronic battery-powered minivans, such as this, are being used by some 60 utilities in the U.S. and Canada in a program supported by the Electric Vehicle Council to demonstrate the feasibility of electric vehicles.

relatively less attention to the demand problem. The tentative conclusions are:

- Even under optimistic assumptions, electric vehicles would not have a major impact on the automobile stock before 2000.
- Electric vehicles should not add significantly to electricity loads before 2000.
- The unclear future of electric vehicles is not due to uncertainty about future prices of energy but to uncertainty about the future initial prices of electric and internal combustion powered vehicles.

Further research is needed to obtain reliable medium-range forecasts of the electricity demands for transportation. EPRI anticipates research within the next year into the demand for personal transportation and the potential role of integrated or automated transportation systems, including all types of mass transit. An EPRI working paper, available in mimeograph, develops a sophisticated, discrete choice model for automobiles, based on performance characteristics. Both this model and the one used by Mathtech are qualitative choice models, but EPRI's model is more sophisticated and uses data on more characteristics. It remains to be seen whether the use of more elaborate demand models will alter Mathtech's pessimistic preliminary forecasts of the market penetration by electric vehicles.

On the issue of the potential role of integrated or automated mass transit systems, EPRI has contracted with Howard R. Ross Associates to investigate the impact of transit systems on electric power consumption in the period 1980–2030 (RP1051). This project will provide a comprehensive overview of the potential use of electricity in all types of transit systems—those in existence, as well as economically feasible future systems—through the first three decades of the twenty-first century. Of particular interest are systems that allow conventional automobiles to be used in a bimodal fashion—on an integrated-automated guideway and also driver-controlled on conventional roadways.
Project Manager: Anthony Lawrence

DATA AND METHODOLOGY DEVELOPMENT

Current projects in the data and methodology development subprogram are directed toward incorporating uncertainty measures into energy forecasting, integrating physical and behavioral sciences and economic and engineering techniques in the study of energy supply, applying measures of reliability to data collection, and developing and analyzing data bases.

A project appraising net energy analysis (RP760) concerns the usefulness of energy analysis concepts. The notion that the energy content of goods and services should be measured originated long ago with scientific and engineering specialists. Since the OPEC oil embargo, the idea has attracted a great deal of public attention. It has aroused the interest of public policymakers and of researchers in a wide range of fields. The Nonnuclear Energy Research and Development Act of 1974 requires ERDA to make an analysis of the net energy potential of nonnuclear technologies on which it sponsors research and development.

Energy analysis is defined, in general, as the computation and measurement of energy flows in society and, in particular, as the quantification of the volume of energy resources embodied in goods and services, directly and indirectly. The basic objective of energy analysis is to measure the efficiency with which energy resources are employed in delivering products to their final use. Net energy analysis, as a part of energy analysis, examines only energy conversion and conservation technologies in terms of their net energy payoff.

Several broad claims are made in support of the importance and relevance of energy analysis. The usefulness of the methodology, however, is the subject of active debate. Many users believe there are severe limitations of energy analysis and confine themselves to special applications. One claim is that energy analysis, particularly net energy analysis, is capable of producing a single summary statistic, comprehensive enough to be used without supplemental information in individual decision making and by policy decision makers. A second claim is that energy analysis reduces all goods and services to a single common denominator that can be applied consistently and without distortion, across time periods, between technologies, and among generations. This claim suggests that energy analysis provides a more reliable and comparable evaluation than dollar evaluations and hence has been extended to embrace an energy theory of value. Finally, claims are made for energy analysis based on three assumptions:

- Energy resources are scarce.
- The scarcity of energy resources increases with the passage of time and the growth of society's activities.
- Society must focus on the consequences of the scarcity and on the actions that create it by employing criteria of physical efficiency rather than of economic efficiency.

Applications of energy analysis

The fields of food production and energy conversion provide examples of the many energy analysis applications that have been made.

In a study of U.S. corn production between 1945 and 1970 (*1*), a downward trend in yield was found, as measured in units of energy relative to energy inputs; that is, the energy benefit cost ratio diminished. Over this period, average corn yield rose from roughly 34 to 81 bushels/acre, while average energy inputs climbed from 0.9 million kcal/acre to 2.9 million kcal/acre. Hence, the energy benefit cost ratio of U.S. corn production declined from 3.7 kcal to 2.8 kcal/kcal of input—a 24% decrease. As a result of this analysis, the researchers recommend consideration of alternative technologies to those presently used in U.S. agriculture, for instance, more labor-intensive methods, substitution of natural sources of nutrients for chemical fertilizers, reduced use of herbicides in favor of mechanical cultivation, minimum tillage, and the development of insect- and disease-resistant plants.

The field of application that most intrigues energy analysts is energy conversion or net energy analysis. Net energy analysis focuses on the efficiency with which primary energy resources are converted to work or to other useful forms of energy. The principal reason for examining the energy conversion industries is that they are the largest consumer of primary energy resources. A study of uranium mining and enrichment processes (*2*) found the results to be sensitive to the size and specifications of a proposed nuclear power plant. Since the uranium fuel input represents the largest single energy investment in the construction of nuclear power reactors, the gross energy requirement of a fuel rod is quite sensitive to the grade of ore originally mined and the degree of enrichment specified for the operation of the reactor. Because significant reductions in ore quality are expected in years to come, the net energy of a new nuclear power plant will decline with time, while at the same time its economic advantage over other forms of generation may increase.

The strong proponents of energy analysis argue that the choice among alternative technologies and public policies should be based only on physical energy efficiencies. Those in the middle ground argue that physical energy efficiencies should be used to supplement monetary evaluation and that both should be used in choosing among alternative technologies and public options. The skeptics say that the results of energy

analysis are already inherent in an economic analysis and that separate analysis is unnecessary.

In research conducted under RP760, difficulties in energy analysis are found to stem from three sources:

- Bona fide doubts that the assumptions and value judgments underlying the analysis are valid and that energy analysis is a more accurate representation of true social and resource costs than economic analysis
- A growing understanding in the scientific community that the energy theory of value is unrealistic and may lead to absurd results
- The diversity of methodologies used by energy analysts, which creates disagreement among themselves as well as among potential users of their investigations

The contractor for this project concludes that energy analysis alone cannot answer the critical question of how to allocate scarce resources now or over time so as to permit equitable treatment of present and future generations. It is also concluded that because of its concentration on the flow of physical variables through the economic system, energy analysis can be a useful complement to economic analysis.

The usefulness of energy analysis can be improved in a number of ways. First, the viewpoint of energy analysis should be broadened to include the flows of other scarce resources such as water, nonfuel minerals, and so on. This broader viewpoint could be called physical resource analysis. Second, energy analysis should adopt some valuation procedure beyond an energy theory of value. Without an explicit or implicit valuation procedure, energy analysis is hampered in answering resource allocation questions. And third, energy analysis should allow for the possibility of factors other than energy being or becoming scarce. A more precise description of technological processes would include the flow of land, labor, capital, and nonenergy minerals. Therefore, to choose among alternative technologies or public policy options, some value should be given to these other inputs. *Project Managers: A. N. Halter and Rex Riley*

References

1. D. Pimental et al. "Food Production and the Energy Crisis." *Science*, Vol. 182 (November 1973), pp. 443-449.

2. P. F. Chapman and N. D. Mortimer. *Energy Inputs and Outputs for Nuclear Power Stations* Milton-Keynes, Bucks, U.K.: Energy Research Group, Open University Report ERG005, September 1974; revised December 1974.

ECOLOGICAL EFFECTS OF ACIDIC PRECIPITATION

The Scandinavian countries are making a major assessment of ecological effects from acidic precipitation. Many lakes and streams in eastern Norway and southern Sweden have been subject to increased acid levels due to acidic precipitation. This appears to be causing a decline in the fish populations in these regions. The extent of the ecological change and the sources of the acid being deposited have been the subject of debate and controversy between several European countries.

Increased acidic precipitation has been observed also in some lakes in the eastern United States. Ecological effects in these regions have been reported that appear to correspond to those observed in the Scandinavian countries. It seems reasonable to assume that the acidification results from deposition, although direct evidence of the mechanisms involved is not available.

Research has indicated that acidic precipitation consists mainly of strong acids (sulfuric and nitric). Since fossil fuel combustion releases relatively large quantities of sulfur and nitrogen compounds, industry has been identified as a possible major source of the acidic materials.

So far, EPRI's Environmental Assessment Department has concentrated its efforts (in the area of fossil fuel combustion effects) on studies of characterization, transport and conversion of effluent species, and potential health effects. Past studies of ecological effects related to fossil fuel combustion effluents have been limited primarily to sponsorship of a workshop, "Sulfur and Biological Systems," which was organized by the Missouri Botanical Garden. This workshop provided a broad background for development of a research program.

Acute effects on individual organisms of exposure to high levels of pollutants, such as SO_2, are relatively well characterized. However, better understanding is still needed of the complex biological, geological, and chemical (biogeochemical) processes in terrestrial and aquatic ecosystems that are supposedly being affected by chronic acidic precipitation in the Scandinavian countries.

The assessment of ecological effects related to deposition of fossil fuel combustion effluents is complicated by a number of factors. On a global scale a number of elements, such as sulfur, are assumed to be released to the atmosphere by natural (biogenic) processes in quantities equal to the anthropogenic (human-produced) input from fossil fuel combustion. Washington State University is undertaking a project (RP856) to characterize and quantify biogenic sulfur emissions for a variety of ecosystem types in the eastern United States.

Another problem is the paucity of long-term chemical and biological data characterizing ecosystems that could be affected by fossil fuel effluents. Without information describing biological and chemical cycles and trends, it is difficult to observe subtle changes in ecosystem function that may be caused by input of fossil fuel combustion effluents.

The Ecological Effects Program is developing an integrated effort to assess effects on ecosystems related to deposition of fossil fuel combustion effluents. The effort will focus on the assessment of vulnerability of different ecosystem types to input of fossil fuel combustion products; the development of a network of calibrated watersheds for measuring fluxes of materials and assessment of long-term effects; and the development of aquatic and terrestrial microcosm systems suitable for assessing deposition effects.

The first phase of this effort will emphasize acidic precipitation. Specific research plans are being developed to investigate possible effects in the Adirondack Mountains. A field project will focus on aquatic ecosystems with the major objective of assessing biogeochemical changes related to lake acidification. As part of this work, sediment profiles in lakes will be studied in an attempt to determine historical aspects of the process of lake acidification. Another project will be initiated to study effects on fundamental biochemical processes of soils of the Adirondack region.

At the same time, a state-of-the-art study will synthesize and critically evaluate data on sulfur biogeochemical cycling in the eastern U.S. The study will identify major information gaps and provide a basis for planning additional research. Ecological effects studies will be closely integrated with other departmental research that relates to questions of identification and quantification of deposition of fossil fuel combustion effluents. These studies include the SURE project (RP862), the biogenic sulfur emissions study (RP856), dry deposition in the SURE region (RP938), plume chemistry in the SURE region (RP860), and the removal of pollutants from power plant plumes (RP858). Research will also be coordinated with programs sponsored by federal and state agencies in this country and with the British and Scandinavian efforts. *Project Managers: Robert Goldstein and Robert Kawaratani*

R&D Status Report
NUCLEAR POWER DIVISION

Milton Levenson, Director

PROCESS COMPUTERS IN POWER PLANTS

Reliance on process computers for surveillance and operation of power plants has increased dramatically as the complexity of plants has grown with the demands for improved availability, efficiency, and safety. In the past, plant process computers were frequently designed as elements peripheral to plant operation, and as a result, computer performance suffered. However, the growing dependence on the newer advanced systems means that any inadequacies may have serious implications for plant operation. Consequently, it is important that past experience be used to enhance the potential for the success of future systems.

Utility experience of this type was recently documented by Macro Corp. in order to provide a better understanding of the problems associated with specifying, procuring, installing, testing, operating, maintaining, and upgrading plant computer systems (RP618). Detailed questionnaires were used to obtain technical information about 334 installations at power plants of 100-MW capacity or greater in the U.S. This is a very high percentage of the plants having computers that were built since 1960 or were under construction. For about half the systems, qualitative information was solicited from the station superintendent, results engineer, chief operator, and project manager. Detailed responses were received from 70% of the individual contacts, permitting the rating of 156 computer systems.

The technical and qualitative information has been compiled, analyzed, and is being published in *Documentation of Utility Experience With Process Computers in Power Plants*, Vol. I and its Technical Compendium, EPRI NP-290. These documents satisfy the following basic project objectives:

- Provide a compilation of power plant process computer types and applications to facilitate interutility communication
- Document utility experience with procurement, operation, and maintenance of these systems
- Formulate and evaluate future R&D efforts relating to process computer applications in power plants

Importance of computer systems

Eighty percent of the power plants that became operational in the last two years had process computer installations. In general, computer systems are an important element in the operation of power plants. The responses from 78 plant superintendents indicated the impact that computer unavailability would have at their plants, specifically: 70% delay startup, 54% hold power generation level, and 22% derate. This level of reliance on the process computer is significant, and it is supported by the responses received from other categories of plant personnel (i.e., results engineers and chief operators). In addition, many of the respondents rated the computer system as being the most important device for determining unit conditions.

All utility respondents were questioned about the goals sought with computer systems or the benefits derived from their use. The responses were somewhat surprising in that the items most often cited were really computer system attributes or computer system functions rather than goals or benefits. It was expected that the respondents would indicate such goals as increased plant availability or improved plant performance. Such operations-related goals were infrequently mentioned, perhaps due to the difficulty in measuring quantitatively the degrees to which they were achieved.

The plant computer systems now operating were judged to be useful by almost all respondents. The respondents identified the following functions as being the most important and helpful to the operator: providing improved process monitoring, alarming, and logging; better operational data; performance calculations; and trending capability. The most often cited problems included inadequacies in the man-machine interface, performance calculation, and turbine startup and control. The last two are functions most often discarded.

Complexity and performance rating

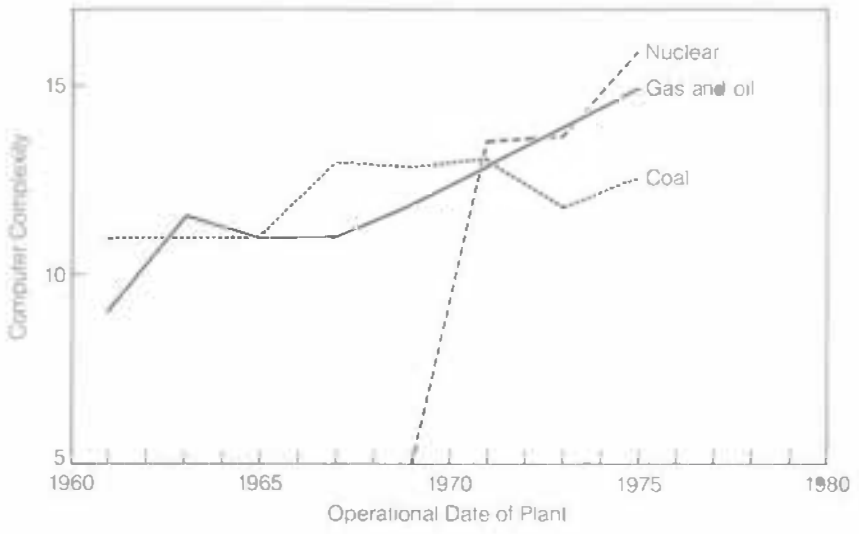
The detailed technical and qualitative information obtained for each computer installation from the various categories of utility respondents was analyzed in a consistent manner to provide a complexity and performance rating for each system. Figure 1 shows the increasing complexity of systems during the past 15 years. The most dramatic change has occurred in nuclear plants. Figure 2 indicates the improvement in the functional performance of these computer installations during the past 15 years. However, when the performance of all 156 rated systems is considered, 33% were judged poor, 50% fair, and 17% good.

The completeness of planning activities associated with computer procurement was found to correlate closely with final system performance rating. For example, all the "good" systems had planning activities, including the establishment of a review committee, while less than half of the "poor" systems had any planning and only a quarter had a formal review committee. Similar, but not as pronounced, correlations were observed for the other computer procurement activities.

Management support

The executive and superintendent respondents strongly supported computer systems in power plants. For example, 100% of the executives felt that plant computers can be a worthwhile investment; 82%, that they improve plant performance; and 90%, that more will be done with computers in future plants. Plant superintendents were equally

Figure 1 The relative complexity of power plant process computers plotted against time tells a striking story of increasing complexity. This is not as marked in coal-fired plants, quite sharp in oil and natural gas plants, and dramatic in nuclear power plants.



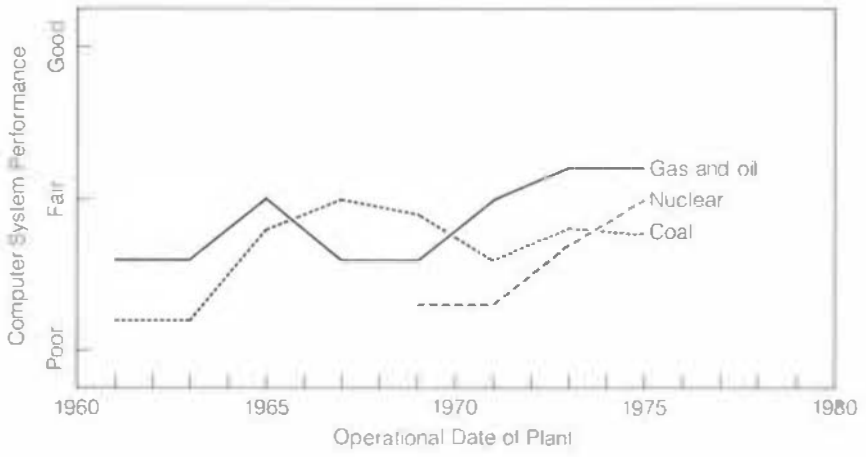


Figure 2 The functional performance of power plant computers has improved over time almost as much as their complexity has increased. Again, nuclear power plants show the greatest rate of change.

enthusiastic, with 92% reporting that computer systems are helpful in the performance of their duties, 93% that they are a positive force in plant performance, and nearly 100% that their operators rely on the computer system.

Future role

The importance of the computer system's role in the power plant is increasing. Each class of respondents included a very high percentage who feel that more should be and will be done with computer systems. Among station superintendents, 88% indicated that they would want a computer system included in any plant to which they might be assigned. At the same time, the total number of computer systems compared with the total number of units installed shows that in the future almost every thermal unit of any significant size will have at least one computer system. However, the successful implementation of these systems will require that the utility industry pay special consideration to certain underlying technical issues. A summary of the current status of advanced computer systems (ACSs) for use in power plants suggests that:

- ACSs are being designed to assist operators with the analysis and integration of plant status information. However, there are few tools available for the quantitative evaluation of the impact of different design alternatives on an operator's performance.
- Adequate data are not currently available for assessing the effects of different control system designs on operator performance or the effects of this performance on plant availability.
- A review of current ACS designs indicates that many have incorporated the concept of functional modularity at the hardware level. This should simplify validation and modification, and help minimize the effects of obsolescence. At the same time, it is noted that there is diversity in the various design approaches and implementation schemes.
- Availability requirements for ACSs will increase as their importance to plant operation is proved. With the improving reliability of computer hardware, software errors may be the major problem in achieving the desired objectives.
- The lack of emphasis on dynamic ACS testing by the domestic vendors compared with other organizations was identified. Does the absence of direct control in domestic applications justify this de-emphasis?

▫ The ability to modify existing process computer systems is judged to be inadequate by many utilities. The flexibility and expansion capability being designed into ACSs should minimize this problem for ACSs.

▫ The more sophisticated ACSs will require increased utility involvement during procurement and subsequently for support. This may present a problem because staffing and training of appropriate utility personnel were judged to be poor at many existing process computer installations.

Based on the results of both studies discussed above, it appears that the application of ACSs within power plants should prove beneficial to plant operation. The increasing complexity of plant control that will be required to maximize availability and still satisfy stringent safety and environmental requirements, plus the continued advances in electronics, will also provide strong impetus for implementing ACSs. With proper attention to the associated problem areas discussed previously, the objectives for these systems should be attained by the industry. *Project Manager: A. B. Long*

FAILURE ANALYSIS AND FAILURE PREVENTION

EPRI is working to define more accurately the reliability of components by analyzing the frequency and severity of malfunctions that result in outages or that have potential safety significance (RP700-1). The project consists of three types of activities:

▫ Failure diagnostics (Task 1), which extracts the detailed information and understanding from performance and failure experience

▫ Methodology development (tasks 2–6), which provides new or improved analytic and experimental tools required to effect improved reliability or cost reductions

▫ Specific engineering applications (tasks 7–9), which utilize existing and improved methodologies to eliminate or reduce the impact of generic problems.

The work is being carried out by Failure Analysis Associates.

Diagnostics

Recent Task 1 failure diagnostic efforts have been concentrated in two areas. First, the pitting, corrosion, and cracking of low-pressure turbine blades have been analyzed to determine whether these phenomena are potentially generic problems. Operational and environmental factors were reviewed in meetings with utility personnel. Detailed laboratory metallurgical analyses of actual blading and specimens exposed in service environments showed concentrations of contaminants known to produce pitting. Significant differences in pitting performance were noted between the blading materials of two major manufacturers. Metallography also suggested that pit corrosion probably occurred during shutdown or startup rather than during steady-state operation. Slight differences in the composition of blade material could contribute; however, significantly different startup procedures specified by the vendors may be even more important.

Second, a review of structural failure potential associated with steam generator tube denting has been initiated. Simplified analytic models of the buildup of corrosion products and their effect on stresses and deformations in the steam generator tubing, tube support plates, and overall assembly (e.g., U-bend areas) have been utilized. The analyses to date predict flow-slot closure and tube stresses to be in excess of yield level. High stresses are calculated in both the circumferential and axial directions, suggesting that both circumferential and axial cracks might occur. However, more rigorous elastic-plastic models, which require numerical solution, are required for verification. Partly as a result of this diagnostic activity, the inspection engineering task (Task 9) has been expanded to provide an extensive effort on eddy-current inspection development.

Methodology

Five technology development tasks have been identified as necessary to achieve the program goal. Task 2 is devoted to improving methods of structural and mechanical analysis, particularly of cracked bodies. Task 3 is developing methods to define the actual component loading conditions and environments; and Task 4 is improving methods to obtain the appropriate materials and initial defects (nondestructive inspection). Task 5 provides in-service evaluation and simulation testing; and Task 6 develops the analytic methods for failure rate prediction and techniques for development of failure prevention strategy.

In Task 2, considerable progress has been made in developing the influence function methods for more accurate and inexpensive analyses of cracked structures. A significant portion of this effort was devoted to developing new influence functions to analyze cracks that might develop in the corner of pressure vessel nozzles. The library of influence functions has been incorporated into an efficient and general computer program called BIGIF.

BIGIF can analyze a wide class of three-dimensional elastic crack problems. When the initial crack size and shape and the materials' subcritical crack growth rate are specified as input, BIGIF can calculate the appropriate crack solutions and numerically integrate the crack growth function to predict flaw extension. BIGIF was applied to an analysis of the BWR feedwater nozzle corner cracking and was shown to be 1000 times less costly than a similar analysis by finite element techniques.

Significant progress has also been made in obtaining simple relationships for the maximum stresses in pressure vessel heads. A new method has been developed that uses asymptotic expansions to obtain approximate solutions for the shell behavior. Approximate results are found to be in close agreement with experimental measurements and with more complex numerical calculations.

In Task 3, actual operational transient experience with nuclear steam supply components has been reviewed for seven plants and compared with the design base loading transients. Differences between the number of design-postulated and actual shutdown transients have been identified. The analyses showed that a plant wear-in time exists during which the number of transients per unit time is much higher. The significance of these differences depends on both the number and magnitude of the temperature and pressure differences. Plant instrumentation systems to record temperature and pressure were reviewed, with the conclusion that additional instrumentation is required to provide sufficient input data for fatigue life evaluations.

In Task 4, improved methods have been developed to define inspection uncertainty directly from field inspection experience or from flawed specimen laboratory inspections. These methods have been applied to analyze the results from two round-robin inspection surveys. Inspection uncertainty analysis has been shown to provide much more quantitative information on inspection reliability. Specifically, inspection uncertainty analysis shows that existing pressure vessel inspection procedures have a very high probability of detecting defects of concern, while the conventional analysis was inconclusive.

Task 4 has also been developing micromechanical models of deformation and fracture. Because the failure of Zircaloy-

clad UO_2 fuel pellets has proved very costly to the utilities, a major portion of the contractor effort addressed this problem. The effort is closely coordinated with projects that EPRI has funded at Stanford Research Institute (RP455-1) and Stanford University (RP456-1), and the joint effort is directed toward understanding and establishing quantitative criteria for clad failure that can be incorporated into operational fuel rod modeling codes. Although some cladding failures have resulted from severe mechanical loadings, these analyses indicate that a generic clad cracking results from a stress corrosion cracking mechanism in the fission product environment.

The approximate models used to date show that crack initiation and the very early stages of crack propagation occupy most of the clad life. Furthermore, interfacial frictional forces between the clad and the fuel pellets, and metallurgical parameters that could be changed within the Zircaloy system, are estimated to have little effect. The feasibility of a microbeam X-ray device to measure crack tip behavior more accurately has been demonstrated, both analytically and with preliminary experimental measurements. Additional substantiation with actual cracked parts is planned prior to assembly of a prototype apparatus.

In Task 5, field instrumentation plans have been developed to determine (1) the fit-up stresses in BWR bypass lines, (2) the stresses and temperatures in both bypass and main recirculation lines, and (3) the temperatures of both metal and fluid and the stresses in BWR feedwater nozzles.

Fit-up stresses have been measured for one stainless steel bypass line during removal of that line from an operating reactor. Peak axial stresses were found to be lower than previously calculated from cold spring measurements made at another unit. Detailed plans have been made for the second and third types of instrumentation, but neither has yet been executed.

In Task 6, improved methods of failure rate prediction have been developed, as have systematic methods of making optimal structural and mechanical decisions with an appropriate balance between risk and cost. Specifically, a new methodology to combine advanced engineering analysis with a limited amount of field operating data has been developed that can accurately calculate reliability and draw definitive conclusions. This method, called combined analysis, has been demonstrated by analysis of (1) rotating turbine equipment to establish a rotor life extension program based on removal for cause and (2) roller bearing failures to establish a cost-effective inspection program. A statistical characterization of a material's properties, required for probabilistic fracture mechanics analysis, has been collected and stored in computer data bases, using concepts from statistical decision theory. Optimized failure prevention strategies have been developed for proof-testing reactor pressure vessels and the trade-off between increased reliability and redundancy in various plant systems.

Engineering applications

Three specific engineering analyses have been performed. Crack initiation from the inner clad surface of the nozzle and subsequent subcritical crack growth into the nozzle wall have been analyzed as a potential failure mode for the BWR feedwater nozzle. The crack propagation part of the analysis uses the general computer program BIGIF developed in Task 2. The statistical reliability analysis has been formulated and a Monte Carlo computer program applied to implement it.

Three separate safety margin parameters have been developed that correspond to vessel rupture, vessel leak, or crack sizes exceeding a specified size for each. The result of this preliminary analysis is the probability distribution of the three safety margin parameters as a function of operation time through the pressure vessel life.

In Task 8, several specific aspects of welding in nuclear systems have been evaluated. First, a weld damage parameter for assessing the resistance to intergranular stress corrosion cracking has been developed further. The damage parameter, which is a complex integral of time and temperature, has been evaluated, using data for BWR piping welds. Weld sensitization is found to be dependent on the number of weld passes and the heat input. Future efforts will attempt to measure directly the degree of damage (sensitization) by standard and potentiokinetic methods. Second, the effect of weld repairs used without subsequent postweld heat treatment in low-alloy-steel pressure vessel materials has been evaluated. Such repairs may become necessary if code-required inspections define unacceptable indications. The alternative methods available for weld repairs have been reviewed and specific needs for additional information have been identified.

In Task 9, controlled reluctance eddy-current generator (CREG) principles have been shown to permit the design of eddy-current transducers with much better resolution and versatility than is possible with present designs. This demonstration effort was expanded to apply CREG principles to develop new eddy-current transducers with improved capabilities for steam generator inspection, including: (1) higher resolution for detection of tube cracking and pitting in the vicinity of the tube support plate, (2) measurement of the degree of denting at support plates and tube ovalization at dents and at U-bends, (3) detection of circumferential cracks, and (4) early detection of crevice corrosion products before denting develops. A CREG probe having the first capability has been fabricated, tested on defective tubes, and evaluated, and it has shown an order of magnitude improvement in flaw size resolution. It greatly improves the inspection capability in and around the tube support plates, compared with the presently used probe. Probes with the other three capabilities are presently under construction or design.

In addition to the nine specific tasks, Failure Analysis Associates has acted as an extension of the EPRI staff in addressing four potential problem areas. They are BWR bypass-line cracking, fuel rod clad cracking, PWR pressure transients, and turbine reliability. The most extensive effort was on stress corrosion cracking in BWR piping. Fracture mechanics analyses were performed to determine the rate of stress corrosion crack growth and the limit load, leak, and rupture criteria for various size lines. Assuming that both small and large pipelines have the same initial flaw size and residual stress distributions, propagation lives should be significantly longer for the large lines than for the small ones. *Program Manager: Floyd Gelhaus*

CORROSION IN LWRs

One aspect of the corrosion and stress corrosion problem in LWRs is the surface film that forms on metal components.

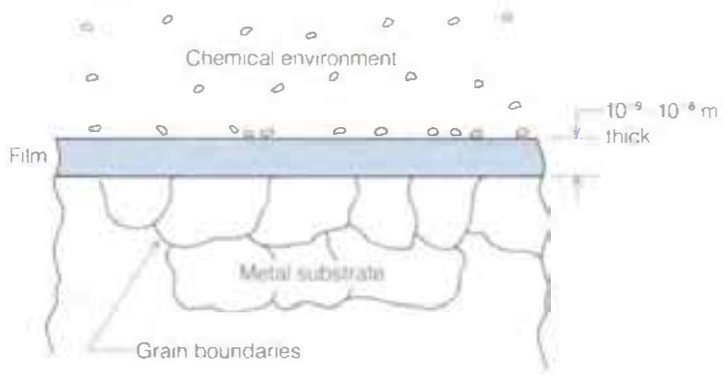
EPRI is carrying out research to define, understand, and predict the behavior of power reactor components when a metal substrate, a surface film, and a chemical environment interact with the component mechanical environment (*1, 2, 3*). Such an interacting system is shown schematically in Figure 3.

The behavior may be divided into two categories: corrosion and corrosion fatigue. Corrosion may be either general or local.

Within local corrosion one may include problems of crevice corrosion, pitting, and stress corrosion cracking. The phenomena of stress corrosion may be considered in terms of initiation and propagation or grouped together in terms of susceptibility. Corrosion fatigue should be evaluated in terms of both initiation and propagation.

The problems of defining, understanding,

Figure 3 A metal-film environment system in a power plant of the kind being studied in the effort to define, understand, and predict the behavior of power reactor components in such an interacting system.



and predicting component behavior may be restated in the form of these questions:

- How is the behavior of metal components in LWRs affected by the environment in which they function? (These environments may be expected or unexpected.)
- How can troublesome conditions be predicted and thereby avoided?
- How can observed problems be corrected?

EPRI's approach to these problems is twofold. The first may be described as phenomenological and involves defining corrosion, stress corrosion, and corrosion fatigue behavior by appropriate testing over the broad range of materials and environments of interest. The second attack is oriented more toward mechanisms and involves developing an understanding of how the metal-film environment elements interact to produce observed behavior. This general understanding is essential to develop a predictive capability and to formulate and evaluate options for corrective action.

EPRI's project with Ohio State University (OSU), one of four parallel efforts (RP311-1), has recently reported 14 findings.

Important accomplishments

- General corrosion technology: Discrete zones of stress corrosion cracking exist as a function of oxidizing potential, temperature, and environmental concentrations. These zones are part of a systematic change in the surface morphology that also includes phenomena of pitting, passivity, and immunity.
- BWR pipe cracking: The stress corrosion cracking of sensitized type-304 stainless steel depends critically on the temperature and oxygen concentration, with an activation energy for 8 ppm oxygen of 100 kcal. The slow strain-rate tensile test has been shown to be a rapid and effective method for obtaining crack velocity data for this system.
- Turbine blade reliability: The type-403 turbine blade material is not significantly susceptible to stress corrosion cracking at 100°C in caustic environments but is very susceptible to stress corrosion cracking in sulfate and chloride environments, regardless of whether the cation is NH_4^+ or Na^+.
- Condenser reliability: Admiralty brass condenser tubing is susceptible to stress corrosion cracking in sodium sulfate solution within the pH range of 2–12 and above potentials of +0.2 V. This indicates that ammonia is not required for such cracking and shows that the presence of oxygen is a critical factor in the performance of condensers.
- BWR pipe cracking as influenced by oxygen: The measurement of electrochemical potential of stainless steel in BWR environments correlates very closely with environments measured in the OSU laboratories. The oxygen dependence of potential at 250°C follows a special pattern involving a jump of about 500 mV in the range of 0.1 ppm oxygen.
- Steam generator tubing reliability: Sulfur segregates prominently to the grain boundaries of pure nickel, Inconel 600, and type-304 stainless steel. Segregation follows a regular dependence on time and temperature. The mobility of sulfur near the surface is greatly enhanced over that of the bulk. Depending on time, temperature, and cold work, other species segregate significantly on the grain boundaries, such as carbon, phosphorus, boron, nitrogen, chlorine, and cadmium.

  The reactivity of grain boundaries with segregated sulfur has been measured in room temperature acid solutions and shown to be approximately 100 times greater than the reactivity of the nickel matrix material.

  Segregation of impurity species to grain boundaries correlates well with that at the surface, permitting the latter to be used as a grain boundary substitute to obtain data more rapidly and economically.

  Using electrochemical measurements, the corrosion kinetics of pure nickel have been defined in phosphate solutions, showing the current at constant potential with the time exponent of the rate as 0.5 or 1, with the higher values progressively found at higher potentials and pH.
- BWR piping reliability: In caustic environments, the corrosion fatigue behavior of type-304 stainless steel exhibits a great reduction of fatigue strength to the point where there is virtually no endurance limit. This contrasts with behavior of the same alloy in acid solutions where an endurance limit is observed.
- Steam generator tubing corrosion: Characterization of the corrosion of Inconel 600, using polarization techniques up to 250°C for phosphate and sulfate environments, shows that pH is the dominating influence on the corrosion rate, with the rate being minimum when the oxide exhibits its maximum thermodynamic stability.
- Corrosion testing method development: The straining electrode has been developed into a major tool for low-temperature and high-temperature autoclave studies of stress corrosion cracking.
- Electrochemical corrosion measurements and monitoring: Techniques for electrochemical measurements of corrosion rates in high-temperature autoclaves have been improved and an important advance has been made in the use of the silver chloride reference electrode, which provides a very reproducible reference in the OSU laboratory. *Project Manager: Thomas Passell*

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R&D Status Report
ELECTRICAL SYSTEMS DIVISION

John J. Dougherty, Director

UNDERGROUND TRANSMISSION

The Underground Transmission Program has recently been redirected as a result of new planning guidelines and new budgets. Specifically, the Underground Transmission Task Force has reaffirmed its commitment to taped cables, with a parallel emphasis on the new manufacturing techniques that will be needed to take advantage of the inherent qualities of cross-linked polyethylene (XLPE) insulation.

In line with this, we are also implementing a search for new polymers that will be applicable to both taped and extruded cables. In addition, the task force has recommended a more relaxed program on cryogenic cable development, with the funds released from this subprogram to be applied to projects involving cable installation and operation. This does not mean, however, that there has been no progress in cryogenics. Los Alamos Scientific Laboratory (LASL) recently achieved a breakthrough in producing Nb_3Ge with losses at 12 K that are comparable to those of the best Nb_3Sn samples at 4 K. This is a factor-of-3 increase in the operating temperature, which is equivalent to a factor-of-27 increase in heat capacity and a factor-of-3 reduction in refrigeration needs. Substantial work remains to be done before this material can be produced in cable lengths, however. A follow-on project with LASL has been under way for nearly a year (RP7855).

Extruded cable systems

The development of 138–345-kV XLPE cable by General Cable Corp. is being augmented by the development of 138-kV splices and terminals to ensure near-term availability of 138-kV systems (RP7829). In addition, splices and terminals rated 230 kV and 345 kV will be developed by General Cable to complete the 230–345-kV systems.

Dc transmission

Work will be undertaken by BICC Power Cables, Ltd., of England to establish the maximum design voltage that can be attained in dc cables insulated with oil-impregnated cellulose paper, currently the best material available for this application (RP7859). This project is predicated on the potential need for very high voltage overhead dc transmission lines by the 1990s. Such overhead lines require matching underground cable for such portions of the transmission corridor where constraints, such as urbanization, preclude the use of overhead lines. The benefits of this project will be twofold: in the near term it will provide information for optimized cable designs at the lower voltage levels; in the long term, it will establish priorities for dc dielectric development. *Project Manager: Felipe Garcia*

Concrete cutting system

Most research and development related to the reduction of costs of underground transmission has been in the area of new, less expensive cable designs that have higher MVA ratings. An area of equal importance is in installation techniques and construction methods. These can account for approximately 50% of installed cable circuit costs.

In an effort to reduce overall installed cable costs, a recently authorized project will undertake to develop an advanced concrete cutting system that uses high-pressure water jets (RP7860). This type of cutting system should be faster, cleaner, and quieter than conventional techniques, such as jackhammers or concrete cutting saws. This water jet concrete cutter uses multiple nozzles, each expelling a continuous stream of high-pressure water at approximately 386.11 MN/m^2 (56,000 psi). At this pressure the cutter should cut a kerf through 8 in of concrete or asphalt-concrete composite. The diesel motors, intensifiers, and accumulators will be mounted on a self-advancing hydraulic vehicle, making the overall system much more compact and requiring a minimum of personnel on site (Figure 1). Flow Industries, Inc., the contractor for this project, has made smaller commercial units in the 37.3-kW (50-hp) range. This unit will be a 186.5-kW (250-hp) cutter.

Soil stability

The optimization of cable thermal performance in the future requires an understanding of the thermal conductivity and stability of the soil along the route chosen; this calls for accurate development of instrumentation for data acquisition pertaining to soil parameters. A project has recently been authorized that will investigate the stability parameters of myriad soil types and develop a thermal probe capable of measuring thermal conductivity, specific heat, and moisture content simultaneously in the field (RP7861). In measuring these parameters along a proposed cable route, one can determine those areas where a thermal bottleneck could occur and where better thermal backfill materials will be needed. Ontario Hydro, which has been a leader in determining soil stability, is the contractor. *Project Manager: Tom Rodenbaugh*

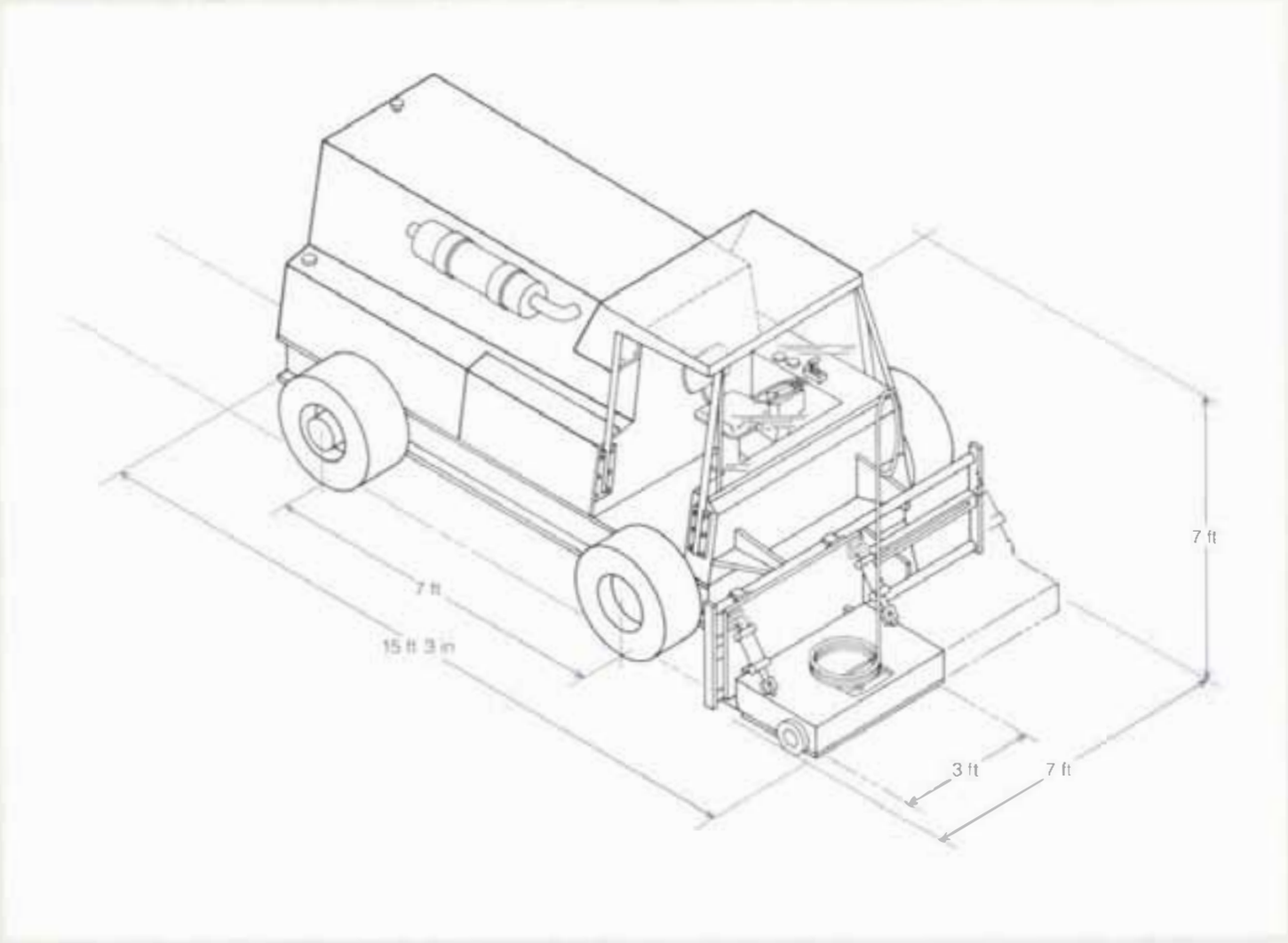
SYSTEM PLANNING, SECURITY, AND CONTROL

To improve the economic operation of power systems, continual changes in electric utility operating conditions require a reevaluation of the methods used to ensure security and provide adequate control. A major incentive for such a reevaluation is the recent escalation of fuel prices, which caused significant changes in power system operating constraints.

The objective of a new effort is to develop advanced methods for reducing the cost of power system operation while retaining acceptable security and control (RP1048). The work has been divided into three problem areas.

The first problem area requires the identification of the key factors needed to analyze the performance of each member of an interconnected power system. This evaluation,

Figure 1 Sketch of self-advancing hydraulic vehicle for cutting concrete with water jets.



called a control performance analysis, must be performed by each member or each control area of an interconnection. In addition, methods will be devised for determining the impact of these key factors on control and operating economy.

The second problem area requires an evaluation of present dispatching methods. An examination will be made of the cost and feasibility of improving the data being used by dispatchers. The project will also evaluate the impact that turbine-generator constraints have on power system operations.

The third problem area calls for an assessment and expansion of the methods now used for planning generator loading and fuel management. Methods for evaluating alternative generation schedules and fuel management, called fuel dispatching, will be developed.

A total of five contracts valued at $1 million have been negotiated to perform the work in these three problem areas.

A two-year, $332,000 effort on control performance analysis will be conducted by Autocon Industries, Inc., (a division of Control Data Corp.) and Northern States Power Co. (NSP). The purpose of this contract is to develop criteria, guidelines, and working tools for analyzing the performance of a control area. Autocon will demonstrate the criteria and guidelines, using NSP data for different system-operating conditions (RP1048-1). It will then translate the criteria and guidelines into working tools for use by dispatchers in daily planning and operations.

The Autocon work will be augmented by the results of a second contract in this area. Philadelphia Electric Co. (Peco) has been awarded a one-year, $107,000 contract to provide a digital power system simulation program for use by Autocon (RP1048-4). Peco will modify a computer program it developed for use on the Pennsylvania-Jersey-Maryland interconnection to study multiarea control performance. At the end of the contract, Peco will conduct a workshop on the use of this computer program for analyzing the performance of a control area.

A separate contract with Peco will be awarded for work in the second problem area, improved dispatch methods. This will be a two-year, $354,000 contract. The objectives of this project are to assess improved methods of representing a turbine-generator (used in economic dispatch) and to evaluate the effects of turbine-generator operating constraints (RP1048-3).

Peco will evaluate the methods now used to determine and update turbine-generator input-output representations. It will research standard test procedures and standard test conditions used to measure input-output curves and will determine the instrumentation and analytic requirements needed to

update the input-output curves frequently. Peco will also identify the various turbine-generator operating constraints that must be considered by the dispatcher and will evaluate the constraints imposed by boiler types and fuel types used. In addition, the impact of equipment limitations and constraints will be assessed.

For the final problem area, fuel dispatching, two contracts have been awarded. A two-year, $158,000 effort concerns the daily fuel dispatching of a pool (RP1048-5). This work will be done by Power Technologies, Inc., in conjunction with the New York Power Pool.

Power Technologies and the New York Power Pool propose to develop an efficient daily fuel-dispatching computer program.

A daily fuel-dispatching procedure should satisfy most, if not all, operating requirements, while optimizing a cost function. The operating requirements to be considered include: constraints on thermal units, such as unit minimum up and down times; operating limits; response rates; limitation of fuel supply; operation of conventional hydrogeneration; a variety of reserve requirements; operation of pumped-storage hydro generation; and transfer limitations for multiarea operations.

A second contract in fuel dispatching has been awarded Boeing Computer Services, Inc. This will be a one-year, $116,000 effort to study the problem of coordinated long-term, mid-term, and short-term fuel dispatching (RP1048-6).

The purpose of this project is to develop a summary of fuel-dispatching requirements for representative utilities, to develop functional specifications for long-term, mid-term, and short-term fuel dispatching, and to identify the most promising algorithmic approaches for developing computer programs for fuel dispatching. *Project Manager: Charles J. Frank*

AC SUBSTATIONS

Power circuit breakers that are designed with today's technology to meet increased power-handling requirements tend to be more complex. They require more interrupters in series for higher voltage and more massive parts for bigger load currents and larger fault current stresses. This all adds up to a greatly increased mechanical operating effort just to meet today's required interrupting times. Interrupter efficiency must be improved to meet these tougher system requirements without imposing the disadvantages of increased size and complexity and reduced reliability.

EPRI is sponsoring work with the General Electric Co. to develop basic information on gas-flow interrupters (RP246). This effort is directed to developing a better understanding of the physical phenomena involved in gas-blast interrupters. The work attacks the greatest problem in gas interrupters, that is, thermal reignition of the arc immediately following current zero due to short-line faults. This problem increases in severity as fault duties become larger.

Work of this nature is not new, and much has been done by many investigators. But lack of coordinated effort by the many investigators has produced information in bits and pieces that do not fit together to provide a complete picture. This project is therefore a four-year effort to coordinate and expand our knowledge of the basic factors affecting arc interruption.

The program will take advantage of scaled-down interrupter models and employs modern analysis of arc physics, aerodynamics, and plasma chemistry to gain insight on the thermal aspect of interrupting problems. The effects of electrode vapor contamination and of nozzle and electrode geometry on arc interruption have been investigated. A limited number of gases or gas mixtures other than SF_6 have been investigated for thermal-interruption performance. Important gas characteristics have been identified and a simplified theoretical model developed for the behavior of the gas-blown arc at the times near current zero. This model is useful in predicting the relative order of performance of gases under investigation. The results of the first two years of effort of this program are covered in the recent EPRI publication *Fundamental Investigation of Arc Interruption in Gas Flows* (EL-284).

The second phase of this program is just getting under way. It will build on the work completed. The investigation of the important axial regions of the nozzle, together with the effects of gas turbulence on interruption, will be made. There will be further study on the effects of gas composition and a study of the transition from thermal to dielectric recovery.

The results of these efforts will enable the switchgear designer to produce more efficient interrupters for today's breaker ratings, as well as to meet future breaker requirements. These designs should be less costly and more reliable because of our new understanding of arc interruption technology. *Project Managers: Narain Hingorani and Glenn Bates*

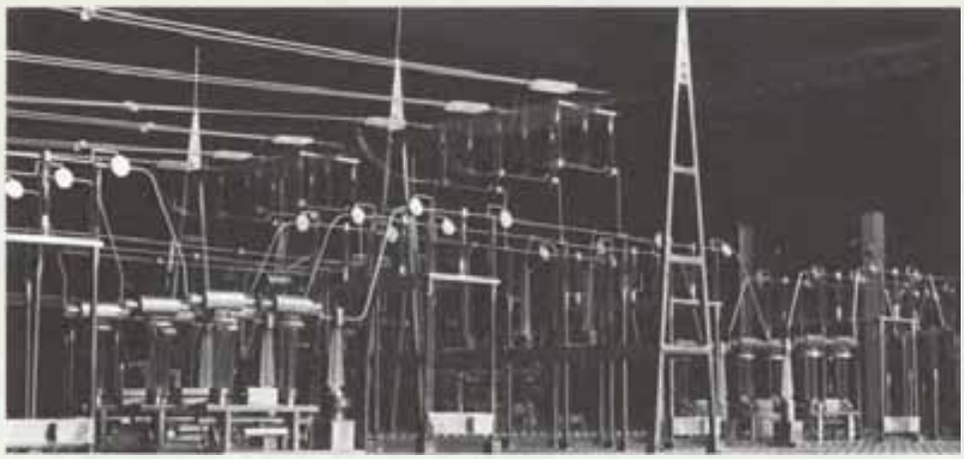
Electric fields

The environmental effects caused by electrostatic fields from high-voltage lines and substations are presently subject to extensive research. Accurate instrumentation and meaningful measuring methods are needed to support such research. Further, it is necessary to be able to predict the field strength that will exist around lines and within substations prior to construction of any new facilities. In recognition of present and future needs, EPRI initiated a model study of electrostatic effects in substations (RP753). The contractor, Ohio State University, has designed and built a scale model of an existing substation within the Columbus and Southern Ohio Electric Co.'s network, developed instrumentation needed to measure the electrostatic fields in the scale model, and verified the model measurements by means of measurements in the modeled substation. These measurements were made with full-scale, 60-Hz instruments of the same type as those used in the model. Conventional, accepted instruments were also used to verify the field measurements. The results to date are very encouraging because the model predictions fall within about 5% of the field measurements in the actual substation.

As is well known, a large substation is structurally very complex. Crisscrossing bus bars, bus supports, lightning masts, buildings, in addition to all the other electrical equipment, perturb the electrostatic field. All these must be considered when one attempts to predict the field at any specific point in or around the substation. A three-dimensional model is obviously necessary and a physical scale model was selected for this study. This approach was deemed to produce the most simple method for electrostatic field prediction. It should be of use to all utilities that have a need to know or wish to modify electrostatic fields at ground level in ac substations.

The scale factor for the modeled substation (Figure 2) is 1:66.7. The voltage scale factor is 1:1000. The field-strength scale is therefore 1:15. The model is energized with a 24-kHz power supply, which gives a frequency scale factor of 400:1. The high source frequency is selected in order to enable use of reasonably sized instrumentation probes for the scale model measurements. The power supply source is, of course, a three-phase system with stable frequency and voltage levels to minimize measuring errors. A miniature capacitive probe and a miniature monopole antenna have been developed and used for model measurement of the vertical component of the electrostatic field at the ground level. Dipole probes and a balanced plate capacitive probe have also been used for free-

Figure 2 Scale model of an existing substation built by Ohio State University to study electrostatic fields in HV substations. Thus far, readings taken in the actual substation on the Columbus and Southern Ohio Electric Co. system have verified model predictions within 5%.



space, electrostatic field, vector measurements. The same types of 60-Hz probes have been used for verification measurements in the modeled substation.

The project has already demonstrated that a scale model made with simple accessories can be used to predict electrostatic fields in high-voltage substations. Ongoing work will attempt to simplify the model further and to investigate the effects of varying heights and spacings and of grounded objects. Then the optimum placement of components for the lowest possible electrostatic field levels in critical high-field strength areas can be determined.

The changes of the electrostatic fields as a result of switch operations will also be investigated. The scale model could become a very useful design tool to utility design engineers. *Project Manager: Stig Nilsson*

DC CONVERTER STATIONS

A key factor in gaining the benefits of HVDC transmission systems is the availability of simple, inexpensive converter valves. All the new dc systems under construction rely on thyristors, which are parallel and series-connected to attain the necessary valve rating. Simplification of the thyristor-firing circuits was recognized as a major step toward simpler, more reliable and less expensive valves. EPRI therefore initiated work to develop a suitable high-power, high-voltage thyristor that can be turned on by means of a light signal applied directly to a light-sensitive area on the thyristor wafer. The light is generated from readily available light-emitting diodes or lasers and brought to the thyristor via conventional, optical waveguides that provide high noise immunity with good insulation integrity.

Two projects, one with Westinghouse (RP567) and one with General Electric (RP669), emphasize different thyristor applications and approaches, even though the two projects have several things in common. Westinghouse has worked on thyristors suitable for a controlled volt-ampere-reactive generator, whereas General Electric has concentrated on thyristors suitable for HVDC valve applications. Basic investigations of the amount of carriers generated by the light versus the wavelength and intensity of the light have been carried out. The parameters affecting the light sensitivity of the thyristors have been studied. The turn-on characteristics and the voltage and current rate-of-change characteristics of the thyristors with many different gate designs (including single and double amplifying gates) have been studied extensively in an effort to reach an optimal performance level of the thyristor.

Investigations of suitable light sources and optical waveguides for coupling the light into the thyristor have been performed in parallel with the thyristor design studies. A significant effort has been spent on the packaging of the thyristors in order to introduce the optical waveguides into the hermetically sealed thyristor package in the most cost-effective and beneficial way (Figure 3). Some studies of self-protection features have been conducted for the HVDC thyristor. It is well known that a thyristor can be inadvertently turned on by a switching surge with a high rate of change across the thyristor. If the turn-on process can be confined to the normal gate area of the thyristor, damage to the thyristor can be avoided. The work has shown that this is feasible, although at present the yield in the production of such a thyristor may turn out to be sufficiently lower, making this feature uneconomical.

Both these projects have reached a point where the feasibility of the light-firing concept has been proved. *Project Managers: Narain Hingorani and Stig Nilsson*

Figure 3 Comparison between a conventional Westinghouse thyristor that has electric gate control (left) and a new thyristor that uses fiber optics for gate control.

R&D Status Report
FOSSIL FUEL AND ADVANCED SYSTEMS DIVISION

Richard E. Balzhiser, Director

FUEL CELLS

The EPRI Fuel Cell Program is now three years old, having been initiated by the transfer of project management responsibility for advanced fuel cell technology from an EEI steering committee to EPRI's technical staff (RP114). During this period, critical issues, both technical and nontechnical, have been identified. A comprehensive fuel cell program to address these issues has been formulated.

The issues

The nontechnical issues critical to the successful commercialization of utility fuel cells were discussed in an earlier issue of the JOURNAL (April 1976), and include:

- Formulating a national fuel cell program to coordinate and focus projects sponsored by EPRI, ERDA, DOD, EPA, GRI, and NASA
- Formulating a mechanism to expedite commercialization of the FCG-1 power plant in conjunction with the support provided by nine utilities and United Technologies Corp.
- Identifying fuel supply and fuel processing scenarios that would permit widespread integration of fuel cells in utility systems
- Defining the role and economics of fuel cell power plants in utility systems

In 1974, EPRI considered three technological options for an advanced fuel cell with the goals described in Table 1. Each option faced critical technical issues, which included:

- The FCG-1 phosphoric acid electrolyte fuel cell required a major breakthrough in electrocatalysis to reduce the heat rate from 9000 Btu/kWh to 7500 Btu/kWh.
- The life capability of the molten carbonate fuel cell was questionable due to the 650°C (1200°F) operating temperature and the corrosive environment.
- The requirement for removal of all carbon dioxide in the alkaline fuel cell reactant streams severely impacted the power plant cost, complexity, and efficiency.
- Conventional methods for processing distillate and heavier fuels to hydrogen-rich streams acceptable to fuel cells were not consistent with the heat rate objectives.

Table 1
FUEL CELL PROGRAM GOALS

Criterion	*FCG-1*	*Advanced Fuel Cell Technology*	
Application	Dispersed generator	Dispersed generator	Central station
Fuel	Naphtha	Distillate or clean-coal liquids	Coal (integrated with a coal gasifier)
Capital Cost (1975 $/kW)	250	200	600 (including gasifier
Heat Rate (full/part load)	9300/9000	7500/7200	7500/7500 (coal to ac power)
Life (years)[1]	20	20	20

[1]Assumes fuel stack refurbishment in 40,000 h.

The program

The EPRI Fuel Cell Program that has been structured in coordination with other U.S. fuel cell activities to address these issues is summarized in Table 2. The National Fuel Cell Coordination Group (NFCCG) has been established, with member agencies expending approximately $50 million annually on terrestrial fuel cells. The ERDA commitment to a substantial national fuel cell program was a key to the formation of the NFCCG and to implementing FCG-1 commercialization activities.

A joint EPRI–ERDA–UTC–host utility project to design, fabricate, install and test a 4.5-MW (ac) module of the FCG-1 power plant was initiated in July 1976. This project will provide for the early verification (on a utility system) of the fuel cell's unique capabilities, provide indications of the system deficiencies, and permit corrections to be implemented in upgraded production power plants. This effort will require approximately $60 million ($42 million for module design and fabrication; the remainder will accommodate installation, test, test support, and technology improvements). EPRI has authorized $11 million for this project.

The fuel supply and fuel cost issue was assessed by Arthur D. Little, Inc., in 1975 and the conclusions were:

- Naphtha, a light hydrocarbon fuel, would be in adequate supply for the FCG-1 through 1985.
- Advanced-technology dispersed generators must be capable of using a wider range of fuels (at least distillates) to ensure an adequate fuel supply.

Table 2
FUEL CELL PROGRAM

Project	*Objective*	*Issues and Priorities*					*Schedule*
		National Fuel Cell Program	Commercialization	Fuel Supply and Processing	Role in Utility System	Technology Goals	
RP842 United Technologies Corp. and host utility	Fabricate and test 4.5-MW fuel cell power plant	2	1	3	3	3	June 1976– June 1980
RP318 Arthur D. Little, Inc.	Determine fuel availability and cost scenarios	2	2	1	1	2	October 1974– October 1975
RP1042 Arthur D. Little, Inc.	Update RP318	2	2	1	1	2	March 1977– October 1977
RP919 Catalytica Associates, Inc.	Determine promising fuel-processing concepts	2	3	1	2	2	September 1976– April 1977
RP729 Public Service Electric and Gas Co.	Assess the fuel cell's role in large utilities	2	2	—	1	2	November 1975– December 1976
RP918 Burns & McDonnell	Assess the fuel cell's role in small utilities	2	2	3	1	2	September 1976– October 1977
RP114 United Technologies Corp.	Develop advanced phosphoric and molten carbonate fuel cell technology	3	—	2	3	1	(Continuous)
RP584 Exxon Enterprises Inc.	Evaluate potential of alkaline technology	3	—	2	—	1	June 1975– December 1976
RP583 Exxon Enterprises, Inc.	Improve phosphoric acid electrode life	3	—	—	—	1	January 1976– December 1977
RP634 Case Western Reserve Univ.	Improve phosphoric acid electrode performance	3	—	—	—	1	June 1975– July 1977
RP371 Northwestern Univ.	Improve molten carbon electrode life	3	—	—	—	1	November 1974– November 1977
RP391 Giner, Inc.	Determine techno-economics of CO_2 removal from fuel stream	3	—	2	—	1	November 1974– November 1975

▫ Coal-derived liquids and gases could not compete economically with petroleum fuels in dispersed generators through 1990.

▫ Central station fuel cells, integrated with coal gasifiers, could be an attractive long-term option.

The Arthur D. Little conclusions have been implemented in the program in several ways. The advanced-technology fuel cell project (RP114) is exploring two variations of commercial fuel-processing techniques that show promise for economical and efficient integration with phosphoric acid and molten carbonate fuel cells. Systems analysis efforts are also conducted on a continuing basis to assess the compatibility of the fuel cell systems with coal gasifiers and, if required, to provide direction to the fuel cell development efforts. To develop the use of distillate fuels, a survey of fuel processing developments in the petrochemical industry is being conducted by Catalytica Associates, Inc. (RP919). Both state-of-the-art and novel concepts employed in the U.S., Japan, and Europe have been reviewed. Several Japanese and European firms have active developments under way to reform heavy fuels (including crude oil). These developments are being analyzed for compliance with program goals and for possible inclusion in the technical program.

The role and economics of fuel cells in electric utility systems is being addressed in two projects. Public Service Electric and Gas Company has completed an assessment of the role of fuel cells in large utility systems, typically those of several thousand megawatt capacity (RP729). A similar effort under way with Burns & McDonnell (RP918) is focused on small utilities (i.e., municipals and rurals with less than 500 MW capacity).

The PSE&G study evaluated the long-range economic benefits of dispersed FCG-1 and advanced fuel cells. The benefits of fuel cells' unique characteristics, such as lower heat rate, relatively flat heat rate characteristic, better availability, reduced construction lead time, and dispersed siting were separately quantified, utilizing reliability, production cost, and optimum generation mix methods familiar in generation planning.

This study concluded that FCG-1 fuel cells are attractive for intermediate duty if the EPRI projected goals of $250/kW installed capital cost, including fuel storage and electrical connections, and 9300 Btu/kWh heat rate are met. The market penetration would depend on factors specific to an individual utility, such as fuel availability and cost, environmental constraints, and load factor, coupled with the relevancy of special fuel cell penalties and savings, such as standby or startup costs (if used daily) or T&D deferrals (if dispersed).

Advanced fuel cells will have significant market penetration at installed capital costs of $200–$300/kW and a 7500-Btu/kWh heat rate. This penetration will probably be constrained only by fuel price and availability. Table 3 gives an example of the study results.

PSE&G also identified average credits of $29–$66/kW as the value of deferred T&D that could result from dispersed siting and $16–$42/kW as the value of the reduced reserve requirements that could result from increased reliability. These credits were not used in the market penetration estimates.

Table 3
FUEL CELL MARKET POTENTIAL
(base fuel price case)

Heat Rate (Btu/kWh)	*Operating Cost[2] (mills/kWh)*	*Capital Cost ($/kW)*	*Special Case*	*Possible Fuel Cell Penetration[3]*
9300	22.79	250	Includes startup cost	0–20%
7500	18.38	350	Nuclear fuel at $0.45/10⁶ Btu	
9300	22.79	250	—	
7500	22.05	200	Nuclear fuel at $0.45/10⁶ Btu and fuel-cell fuel at 20% premium	20–40%
7500	18.38	300	Nuclear fuel at $0.45/10⁶ Btu	40–65%[4]
7500	22.05	200	Fuel-cell fuel at 20% premium	
7500	18.38	200	—	75–80%[4]

Source: EPRI EM-336 (RP729), prepared by Public Service Electric and Gas Co.

[1]Base fuel price case from RP318, Arthur D. Little, Inc.
Nuclear $0.60/10⁶ Btu
Coal $1.20/10⁶ Btu
No. 2 Oil $2.45/10⁶ Btu
No. 6 Oil $2.05/10⁶ Btu

[2]Operating cost (fuel only) = heat rate (Btu/kWh) × $\frac{\text{No. 2 oil price (\$/10}^6\text{ Btu)}}{1000}$

[3]Credits for such fuel cell characteristics as dispersed siting (T&D deferred) and increased availability are not included.

[4]It is likely that the fuel supply will constrain market penetration at 40%.

The advanced-technology fuel cell research has focused on resolving the molten carbonate and phosphoric acid technical issues (RP114). Significant progress has been made in molten carbonate technology since 1974. The highlights include:

- Demonstration of the cell voltage required for a heat rate of 7500 at power densities consistent with the desired capital cost
- Operation of small single cells for 12,000 hours
- Identification and solution of two life-limiting mechanisms
- A 1400-hour test of a stack of nineteen 1-ft² cells, operated in a self-sustained mode (outside an oven) to verify the thermal management model

The major advanced phosphoric acid development was the identification and verification of a new, low-cost stack concept.

The potential of the alkaline electrolyte fuel cell to meet the advanced fuel cell goals was assessed by Exxon Enterprises Inc. (RP584). At the time, Exxon was involved with Alsthom (France) in the world's second largest (to United Technologies Corp.) terrestrial fuel cell activity. A detailed systems analysis effort focused on minimizing the cost and heat rate by optimizing carbon oxide removal and heat integration within the system. The study concluded that (1) the advanced heat rate goal could be achieved, but capital cost projections were considerably above target; and (2) the alkaline fuel cell would require considerable R&D to meet cost, performance, and life objectives.

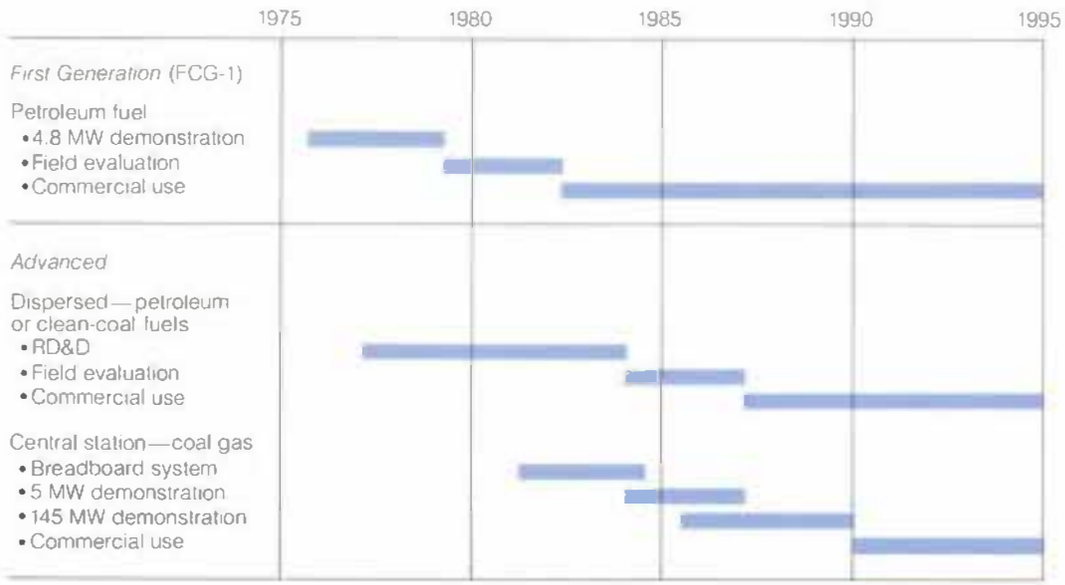
Based on these conclusions, it was mutually agreed that the alkaline system was not a viable option until fundamental fuel cell electrode problems were resolved.

Program plans

Under future budget constraints, only one advanced fuel cell technology can be supported at the level required for successful implementation. The molten carbonate fuel cell has been selected as the advanced concept, based on its rapid technical progress and demonstrated capability to meet heat rate goals. The low-cost, phosphoric-acid stack will be transferred to the 4.5-MW FCG-1 module demonstration project. Some R&D support for phosphoric acid will be continued; these plus iterative improvements made in production may reduce the FCG-1 heat rate significantly. Fuel-processing efforts to expand the range of fuels that can be used in fuel cells will be continued. This effort supports both the advanced-technology and the FCG-1 dispersed generators.

Because a single advanced-technology approach offers substantial risk, EPRI will participate in (cofund) a parallel molten carbonate activity initiated by ERDA, managed by Argonne National Laboratory, and involving a group of contractors, which include the Institute of Gas Technology, Energy Research & Consultants Corp., and General Electric Co.

Figure 1 The fuel cell program is geared to the commercial introduction of first-generation units in the early 1980s, followed by advanced dispersed power plants in the late 1980s and coal-integrated systems in the early 1990s.



Time line

The projected time line for the fuel cell program is shown in Figure 1. The FCG-1 will enter commercial service in 1982–1983. This will be followed by the advanced power plant in 1987–1988. EPRI is now evaluating meaningful coal integration scenarios that will use the molten carbonate concept. This power plant will probably not be commercially available prior to 1990. *Program Manager: Arnold Fickett; Project Manager: Edward Gillis*

SOLAR PHOTOVOLTAIC ENERGY CONVERSION

Over the past two decades, the direct conversion of sunlight to electricity with arrays of photovoltaic devices has developed into a well-established technology for extraterrestrial electric power applications. During the past several years, a small, terrestrial market for photovoltaic arrays has also emerged, based principally on remote power applications. However, these arrays are at present very expensive power sources, and the total annual market for all types of photovoltaic devices does not exceed several million dollars and several hundred kilowatts. Nevertheless, the generation of electricity directly from the light of the sun with no intermediate thermal machinery has a strong innate appeal, owing to a greatly reduced dependence on moving parts and the attendant possibility of reduced operating and maintenance requirements. A number of research and technology programs are currently under way, both in the U.S. and abroad, aimed at reducing photovoltaic array costs to levels that would allow economically viable, large-scale applications. ERDA, through its solar photovoltaics program, is a principal supporter of much of this activity, and several programs are operating with corporate support. ERDA's FY77 photovoltaics expenditures are estimated at $35 million.

EPRI's photovoltaics activities are, at present, aimed primarily at assessment of future potential prospects for photovoltaic conversion devices. Project activities are intended to complement federal efforts, with electric utility requirements and impacts as one prime focus. An early goal of EPRI's efforts is the development of a set of cost and performance objectives that photovoltaic cells and arrays need to achieve for central power deployment in order to reach thresholds of economic viability. These objectives are being expressed in terms of allowable array and cell costs per unit area and required conversion efficiencies, rather than the cost per peak kW designation that is commonly used. (Array output in peak kW is obtained only at solar noon on a clear day with the array perpendicular to the sunrays.) Cost per peak kW is very misleading since it does not allow the estimation of total power plant cost and is often erroneously interpreted to *be* that total cost. One important component of any photovoltaic power plant that has often been overlooked is array support structure, including land, site preparation, anchoring, and wiring. Its contribution to total plant costs will be substantial and cannot be estimated unless conversion efficiencies are known.

The ERDA program

The ERDA photovoltaics program has several major thrusts. By far the largest, funded at a level of approximately $20 million in FY77, is a silicon technology program that is aimed at substantially reduced single-crystal silicon array costs and greatly increased production capability. The approaches are primarily engineering development and market stimulation and include a series of scheduled array purchases, which, although small by electric utility standards, are sizable

for the photovoltaics industry. The ERDA photovoltaic program cost goal for large-scale production of single-crystal silicon solar cell arrays is $500/peak kW by 1986. This cost objective is based on a "learning curve" projection, using the solid-state device industry for comparison. Even though scientific similarity exists between silicon solar cells and other solid-state devices, the learning curves of other solid-state devices reflect the reduction in labor and materials achieved through large-scale reduction in physical size of the devices and not merely an increase in production output. Because solar cells must capture the diffuse solar radiation, large array areas must be deployed, thereby limiting the potential for reduction in size to only the thickness of the solar cell. Consequently, significant doubt exists about the feasibility of achieving the cost objective of $500/peak kW, regardless of the size of the increased production the ERDA program plans to finance.

Other thrusts of the ERDA program include efforts to reduce photovoltaic cell costs through deployment of solar flux concentration; systems applications and conceptual design studies; experimental field test and applications projects in the public, private, and military sectors; and an R&D program in advanced photovoltaic materials, which has been relatively small but is now growing.

EPRI R&D

Large-scale utility applications of photovoltaic systems are not likely unless one or more major advances occur in photovoltaics research, technology, or economics. Through its efforts in photovoltaics, EPRI intends to maintain an informed position on the state of the art and to ensure that electric utility industry requirements are made available to the federal photovoltaics program. At present, a number of photovoltaic devices and systems based on a variety of semiconducting materials and deployment schemes are under investigation. Since none of these has yet demonstrated superior potential for achieving economic viability in large-scale applications, it is necessary to maintain balanced R&D efforts, with support for a number of options at above-critical levels. EPRI plans to maintain the flexibility to investigate novel, promising approaches as they arise. Both the in-house development of objectives and contracted assessment efforts are providing key inputs for setting priorities and establishing the perspective with which the significance of developments can be measured. EPRI has at present no activities in conventional single-crystal silicon technology, since preliminary EPRI assessment indicates that the single-crystal silicon potential for large-scale electric utility applications is remote, and ERDA is already adequately funding this area.

Thin-film photovoltaic devices appear to have potential for low cost. These devices require one to two orders of magnitude less photovoltaic material per unit area than single-crystal silicon photovoltaic devices. However, their performance to date has been inferior to that of silicon. An assessment of the most developed of these, copper sulfide–cadmium sulfide cells, has been carried out for EPRI at Brown University. This assessment concludes that cadmium sulfide, thin-film devices have sufficient potential for achieving acceptable costs and performance to warrant an extensive R&D program. The assessment suggests a broad outline of program activities. A number of these activities are in progress with federal and corporate support.

The EPRI effort will determine nominal cost and performance objectives for central photovoltaic power plants which, when combined with several hours of storage, can serve intermediate loads. Such plants typically might displace scarce, expensive fuels, such as oil and gas, not competing with conventional baseload generation plants, but complementing them, allowing the achievement of the high overall grid reliability requirements typical of electric utility systems. The objectives for photovoltaic power plants are based on conditions thought to reflect the threshold of economic viability and therefore probably indicate upper limits on the value of these power plants relative to today's perception of long-term economic conditions. These objectives will be reviewed as changes occur in photovoltaic and conventional generation technologies and economics.

Cost versus efficiency

The objectives are expressed in terms of allowable installed costs per unit of active solar flux aperture area as a function of the annual average insolation collected and the overall photovoltaic power plant efficiency for different deployment and tracking configurations. These area-related costs include photovoltaic devices, concentrators, array support structures and sun-tracking devices, land, site preparation, and interconnecting wiring. These costs will make up the major part of total power plant costs. The key parameter in describing total power plant costs is the ratio of the area-related cost per unit aperture area, C_A, to the product of the annualized average insolation collected per unit aperture area, I_{avg}, and the overall power plant efficiency, η_{pl}. Preliminary objectives are based on a hypothetical photovoltaic central station serving intermediate loads, assuming a 1990 time frame and levelized busbar energy cost of 60 mills/kWh in 1976 dollars. This busbar energy cost leads to a total plant cost of $1650/kW (rated) at a 50% capacity factor and a value of the key parameter $C_A/\eta_{pl}I_{avg}$ of $1600/kW (avg). The average insolation collected varies with the deployment scheme, with generally higher values as the degree of sun-tracking increases. In addition to the cell efficiency, the overall plant efficiency reflects losses associated with other plant components, such as inverters, storage, and wiring, and includes optical losses in concentrators, if these are employed.

Preliminary cell efficiency objectives have been obtained for several deployment schemes currently under consideration, assuming operation in a high-insolation, southwestern U.S. location and using support structure costs judged to be realistic. Flat panel, fixed-tilt-angle arrays will probably require panel efficiencies of 15% if panel installed costs near $30/m² can be achieved. Panel efficiencies below about 10% would probably preclude viability, even if panel costs of only several dollars per square meter are coupled with optimistic values for support structure costs. On the other hand, high-concentration, two-axis tracking systems having additional costs associated with concentrators and tracking devices, as well as increased optical losses, will probably require cell conversion efficiencies near 30%. These systems would allow the use of expensive cells, since required cell areas and therefore cell costs per unit aperture area would be greatly reduced. Low-to-medium concentration systems, requiring only single-axis tracking, would require about 25% cell efficiencies if cell costs could be insignificant. Even compound parabolic concentrating systems may require efficiencies near 25%, since reduced support and tracking requirements are offset by cell costs that cannot be negligible because very low concentration ratios (about 3:1 to 5:1) need to be employed if continuous tracking is to be avoided.

Even if the 1986 silicon goal is achieved, it falls far short of the above objectives. The $500/peak kW corresponds to a panel price of $75/m² at 15% panel efficiency, to which costs for delivery and installation must be added. Also, the higher efficiency objectives

for the concentrating schemes are beyond the practical achievable limits of silicon. To date, no device has been identified that approaches these efficiencies, though several possibilities have been proposed. Achieving these efficiencies will probably require expensive photovoltaic devices, indicating very limited value for low and moderate concentration schemes—for which cell costs would not be insignificant—unless unforeseen substantial reductions in support, tracking, or concentrator costs can be achieved. Cells employing gallium arsenide are under development, and these may reach efficiencies in the 20–25% range, but their costs are expected to remain high. As a result, their use would probably require high concentration and two-axis tracking, causing even these attractive efficiencies to fall short of the above objectives.

These cost and performance objectives, therefore, suggest two principal avenues to economic viability in large-scale applications of photovoltaic devices: activity aimed at very low cost, flat photovoltaic panels with acceptable efficiencies, and activity aimed at very high-efficiency devices intended for high-concentration applications. Thin-film photovoltaic devices have demonstrated efficiencies up to about 8%. Developmental efforts have been initiated with potential for achieving 10% and possibly greater efficiencies. This, when coupled with the low-cost potential of these devices, indicates that thin-film activities should rank very high on a scale of photovoltaics R&D priorities. Hence the recent growth trend in ERDA thin-film photovoltaics activities is a positive development and should be encouraged.

At present, the second avenue is receiving less attention, partly because only a very few candidate schemes have been identified. One approach of this type is being assessed under EPRI support at Stanford University, where a research team is investigating thermophotovoltaic (TPV) conversion with silicon photovoltaic cells (RP790). This is a high-risk project, but if successful, the payoff may be high. In concept, TPV conversion employs a high-temperature radiator that is heated by highly concentrated sunlight and combines spectral shifting with infrared energy recycling to give greatly increased cell conversion efficiencies. Potentially achievable cell efficiencies are thought to be in the range of 30–40%, and the Stanford effort is aimed at determining experimentally whether these cell efficiencies can actually be reached.

Other key issues that will need to be addressed if experimental results are favorable include concentrator performance, overall concentrator-converter-cell energy balance, including cooling requirements, and high-temperature radiator durability and lifetime. After several preliminary experimental runs, TPV cell efficiencies of 12% have been achieved. Subsequent experiments with test diodes have isolated two major problem areas and have led to preliminary improvements, which, when transferred to completed TPV cells, are expected to double the efficiencies. At present, no major impediment precluding the predicted high efficiencies has been identified.

System evaluation

An additional key element in EPRI's assessment of photovoltaics is a utility-oriented requirements assessment of photovoltaic electric power systems by the General Electric Company (RP651). This project is aimed at a detailed assessment of the value of photovoltaic systems in several utility systems representing different geographical regions. Photovoltaic systems are being compared with conventional generating apparatus for supplying incremental system load, using detailed utility industry methodology for generation expansion planning, including system loss-of-load probability, production costing, and investment analysis. Major photovoltaic system characteristics are treated parametrically, including costs, performance, penetration, array aggregation level—from residential units to central stations—and storage capacity and type. Principal results are expected to include a detailed set of photovoltaic components and systems cost and performance objectives for each utility system studied, and an assessment of the impacts of the photovoltaic systems on these utility systems as functions of the degree of success in meeting these objectives. Recommendations will also be made on R&D needs and priorities. Utilities cooperating with this study are located in Arizona, Florida, and Massachusetts. Project completion is scheduled for later this summer.

The potential environmental impacts of photovoltaic central power plants are being addressed as part of an environmental assessment of major solar central station alternatives. This study, being carried out by Black & Veatch, consulting engineers (RP955), will identify both primary and secondary environmental impacts of alternative photovoltaic systems and is expected to be useful to utilities in preparing the technological alternatives section of the environmental impact statement for conventional power plants. *Project Manager: Edgar A. DeMeo*

SO_x CONTROL

The objective of the EPRI SO_x control subprogram is to support the utility industry in developing the most cost-effective technologies for controlling SO_x emissions. Environmental regulations for the remainder of the century are forecast to be about 90–95% emission control for coal-fired sources, even in the face of growing controversy over the validity of the basis for such standard. The EPRI SO_x control subprogram provides a central technical support capability for the large and growing capital commitment by the utility industry to flue gas desulfurization technology.

Unless much more stringent control levels are required, flue gas desulfurization (FGD) is, and is expected to remain, the least expensive option for continuous control of SO_x emissions for direct coal-fired plants. EPRI's efforts will be primarily compiling, evaluating, and communicating the massive industry data base in FGD technology and providing test, design, hardware development, and field technical service to the industry.

This program will initially emphasize providing the site-specific design and operating bases that will allow the utility industry to implement its current $4 billion (40,000 MW) lime/limestone scrubbing commitment with the least impact on power plant performance, reliability, and operability. Longer-term emphasis is on (1) supporting the development and demonstration of improved FGD systems that minimize by-product disposal, water pollution, and land use impact at a capital cost of $100–$200/kW (1975 dollars); and (2) maintaining data on the state of the art and associated cost of SO_x control technology so that the utility industry can evaluate the cost-benefit trade-offs of various levels of control. Wherever possible, EPRI will monitor utility-sponsored demonstration projects and participate in testing new processes, making useful data available to the industry.

Program objectives

Specific objectives to be achieved are:

- By 1978, establish and operate prototype-scale scrubber development and evaluation centers for both eastern and western coal.
- By the final quarter of 1978, develop the design and operating support basis that will allow the utility industry to confidently purchase, if necessary, large-scale, closed-

loop, lime/limestone scrubber and associated by-product disposal systems for high-sulfur coal combustion.

□ By 1980, complete the pilot-scale (20–50 MW) development, tests, and evaluation of advanced regenerable stack gas desulfurization processes on coal-fired facilities.

Lime/Limestone FGD

EPRI's Air Quality Control Program has funded a number of projects that will provide a firm data base for lime/limestone scrubber design. Battelle, Columbus Laboratories evaluated the scrubbing installations across the U.S. (RP209). This project summarized the state of the art of lime/limestone scrubbing technology and highlighted a number of major generic problem areas that restricted the performance, reliability, and cost of this technology. To address these problems, the EPRI program has focused on each of the subsystems that make up a scrubber. These subsystems, which include reheaters, demisters, contactor-absorbers, recycle tanks, and dewatering devices must be designed properly to ensure their individual reliability and thus the reliability of the entire scrubber system. However, making the situation even more complicated, each subsystem must be designed to incorporate site-specific variations stemming from the high degree of chemical variability in coal. Thus the success of a scrubber at one location does not ensure its success at another site.

Each scrubbing system must be a site-specific hybrid, incorporating subsystems; no single lime/limestone scrubbing system will satisfy the SO_2 emission requirements of the utility industry.

EPRI has recently completed unit studies on two subloops identified in the Battelle-Columbus report as limiting lime/limestone scrubbing capability—mist eliminators and reheaters.

An improperly designed mist eliminator builds mudlike solids and scale on mist eliminator blading (Figure 2). This plugs the assembly and requires the shutdown of the entire scrubbing system for cleaning. Good mist eliminator design results in lower operating costs by minimizing the amount of moisture carryover that requires reheating along with the scrubbed flue gases. Excessive moisture carryover can result in a significant waste of energy in the reheaters. However, in attempting to minimize the carryover of moisture from the demister, the design engineer may design a demister subloop that plugs easily. This and other trade-off problems are addressed in the report *Guidelines for the Design of Mist Eliminators for Lime/Limestone Scrubbing Systems*, EPRI FP-327.

The report evaluates 15 parameters that must be considered in designing a reliable and efficient mist eliminator. It also summarizes the operational experience with mist eliminators of all scrubber systems presently operating in the U.S. The problems encountered with these operational mist eliminators and the design parameters that would have minimized or eliminated them are described.

After a flue gas is scrubbed, it is reheated from a saturated temperature of about 52°C (125°F) to a stack exit temperature of 80°C (175°F) to avoid downstream condensation, visible plume, and/or to disperse emissions. Reheating a scrubbed flue gas is the major energy requirement of a scrubbing system (which amounts to 25–50% of the scrubbing system's energy needs). This can account for 1–3% of the total boiler output. Any savings in energy requirements for reheat will result in substantial decreases in operating costs of scrubbers. In a second unit study recently completed, *Stack Gas Reheat for Wet Flue Gas Desulfurization Systems*, EPRI FP-361, guidelines are given on how to select the most efficient (energy input) reheater system for reheating a stack gas. The study evaluated reheat methods currently in use: in-line reheat, indirect hot air reheat, and direct combustion reheat. It was determined that the reheat temperature required depends on the objective for the reheat, while the minimum heat requirement depends on the degree of reheat, the method, and the quantity of mist carryover from the scrubber.

The smallest amount of reheat is needed when only the avoidance of downstream condensation is required. (An in-line reheater requires the least energy.) The minimum calculated heat requirements for avoidance of downstream condensation showed that the indirect hot reheat and the direct combustion reheat required 12% and 18%, respectively, more heat input than that provided by in-line reheat.

A third unit study examined the relative performance of existing and innovative absorber designs. Of particular interest is the evaluation of a new contact-absorber using cocurrent flow (gas and scrubber liquor injected in the same direction) while scrubbing a flue gas, rather than the commonly used countercurrent mode. The cocurrent contactor-absorber tower is able to scrub gases having a through velocity of 5.8 m/s (19 ft/s). Most scrubbers are designed for gas velocities of 2.5–3.0 m/s (8.5–10 ft/s). Therefore, smaller and fewer contactors are required and capital costs are reduced. The testing was performed on a 1-MW pilot plant at TVA's Colbert Power Station. Results indicate that the sulfur dioxide removal efficiencies are equal to those obtained by conventional countercurrent scrubbers but at much lower power. A project has been initiated to incorporate a 10-MW cocurrent scrubber in the advanced FGD development and test facility at TVA's Shawnee plant when the operation of the facility becomes the responsibility of EPRI in 1978.

Figure 2 Side view of mist eliminator after 134 hours of operation. Improper design of mist eliminators results in pluggage, requiring frequent cleanings.

Utility industry operation of the Shawnee facility will provide a versatile, highly instrumented test bed for developing scrubber system technology under coal-fired utility operating conditions and at a scale that permits the results to be readily transferred to utility practice. EPRI also plans to operate two additional scrubber configurations: a countercurrent venturi-spray tower operated with lime/limestone and a double alkali system, using basic aluminum sulfate as a reagent with lime/limestone for regeneration. The Shawnee test facility will test totally integrated scrubbing systems whose design and construction incorporate the subloop philosophy.

Developing the technology of lime/limestone scrubbing by this subsystem approach should establish a firm data base to allow confident design of scrubber systems where they are required. To communicate this data base to the utility personnel who are in the most need of it, a project has been initiated in the Air Quality Program to compile and publish a lime slurry data guidebook. The

Table 4

EVALUATION SUMMARY OF REGENERABLE FGD PROCESSES

Process	*Company*	*Demonstration Size (MW)*	*Main Advantages*	*Remaining Concerns*
Carbon adsorption				
Moving bed[1]	Bergbau-Forschung; Foster-Wheeler Energy Corp.	20	Dry; uses coal as direct reductant; prototyped	Much solids handling; hot spots in adsorber; proving Resox
Fluidized bed[2]	Westvaco	0.2	Dry; relatively simple	Fluid-bed operation; Sulfate emission; requires H_2; absorbent attrition
Copper oxide[1]	Shell-UOP	40	Dry; very good for NO_x; prototyped	High capital cost; highest energy consumption requires H_2; mechanically complex
Sodium salt scrubbing				
Thermal regeneration[1] (Wellman-Lord)	Davy Powergas	220	Good SO_x removal; well-developed, simple operation of absorber	Wet; sulfate waste produced; gaseous reductant required
High-temperature reduction[2]	Atomics International Div., Rockwell International Corp.	1–2	Semidry; uses coal as direct reductant	Delicate absorber control; high temperature in reducer; particulate control
Electrolytic regeneration[1]	Ionics	0.75	May provide backfit sodium regeneration	Wet; gaseous reductant required; high power consumption; weak sulfuric acid as by-product
Citrate as buffer (or phosphate)[2]	Pfizer, Inc.; Peabody Engineering Corp.; Chemico Div., Envirotech Corp.	1	One-step sulfur production; no concentrated sulfur dioxide stream as a gas	Difficult product separation; hydrogen sulfide required as reductant; wet
Ammonia scrubbing				
Thermal regeneration; sulfur dioxide reduction[2]	Pullman Kellogg Div., Pullman Inc.; Catalytic Inc.-IFP	30	Excellent sulfur dioxide removal; prototyped; simple sulfur dioxide reduction	Fume potential; syngas required as reductant; wet
Bisulfate regeneration[1]	TVA	1.2	Low liquid-to-gas ratio; good absorption	Fume potential; bisulfate very corrosive; wet reducer operation
Magnesia scrubbing[3] (mag-ox)	United Engineers & Constructors, Inc.; Chemico Div., Envirotech Corp.; others	160	Relatively simple; prototyped	High-temperature operation; wet
Catalytic oxidation[3] (Cat-Ox)	Monsanto Co.	110	Simple; low labor cost; dry	High cost; sulfate emission; electrostatic precipitator required; mechanical operation
Lime/Limestone scrubbing				
Calcium sulfite–sulfate reduction[3]	Various	(Absorber) 800+	Known scrubbing; regeneration loop can retrofit	Wet; high-temperature, high-cost regeneration

[1]Either sulfur or sulfuric acid can be produced as by-product
[2]Only sulfur as by-product
[3]Only sulfuric acid as by-product

information presented may be used to supplement the knowledge of those familiar with utility operations but not with chemical operations. Specifically, the guidelines will technically integrate and summarize the combined results of the extensive utility, architect-engineer, vendor, EPA, and EPRI investment in the development of lime scrubbing technology. The results will permit a utility to forecast realistically the performance, reliability, and maintenance characteristics that can be expected for alternative lime scrubbing system designs as a function of site-specific variables. Such a forecast can be used by a utility to improve the quality of bid specifications, as well as to improve its capability to judge the responses received.

Table 5

FGD: ENERGY USAGE AND COST

Process	*Energy Penalty (Btu/kWh)*	*Total Utility and Raw Material Costs (mills/kWh)*
Copper oxide	1420	4.0
Sodium salt scrubbing (electrolytic regeneration)	1160	2.4
Ammonia scrubbing (bisulfate regeneration)	1030	2.5
Carbon absorption (fluidized bed)	950	3.1
Carbon absorption (moving bed)	900	2.3
Ammonia scrubbing (thermal regeneration)	860	2.0
Sodium salt scrubbing (thermal regeneration)	840	1.7
Sodium salt scrubbing (high-temperature reduction)	670	1.2
Sodium salt scrubbing (citrate or phosphate as buffer)	670	1.4
Magnesia scrubbing (acid production)	604	1.2
Lime/Limestone scrubbing	380/390	1.1/0.8
Catalytic oxidation (Cat-Ox)	290	0.5

Regenerable flue gas desulfurization

In line with the specific objectives of the SO_x control subprogram, EPRI's work in regenerable flue gas desulfurization has been set up to complement the lime/limestone work. It provides options for improved SO_2 removal, reduced water pollution and solid waste impact, reduced raw material use, and lower cost systems at specific sites. The EPRI development approach is progressing from (1) process comparison and technical evaluation to (2) detailed site-specific design and then to (3) construction and testing of an appropriately sized demonstration facility. In addition, EPRI is evaluating full-scale demonstration plants in conjunction with the host utilities.

The first step of the development work has been published in a report by Radian Corp., *Evaluation of Advanced Regenerable Flue Gas Desulfurization Processes*, Vol. I and Vol. II, EPRI FP-272, which reviews emerging processes and evaluates 12 systems, including 3 that have been tested on a large scale (Wellman-Lord, magnesia, and Cat-Ox) and lime/limestone as a baseline. The report evaluates sludge regeneration from the lime/limestone scrubbing, sulfur versus sulfuric acid production, and gasifier problems. It has chemical, mass, and energy balances for the processes and puts the systems on a common design basis. Operating costs were calculated, but detailed capital costs were not estimated because the processes differ widely in their state of development and the comparative equipment costs would not be realistic without more detailed estimates.

Some general results of the evaluation are:

- Calcium sulfate/sulfite sludge regeneration is not currently practical due to cost, energy use, and chemical complexity.
- The magnesia and Wellman-Lord systems are further developed and are not inherently inferior to other less-developed regenerable processes.
- The less-developed processes have specific advantages in various subsystems of the process, but these processes require more development at pilot or prototype scale before being confidently installed commercially.

Each FGD system under evaluation has unique design features that present potential advantages and problems in acceptance of the process by the electric utility industry. A list of FGD processes, their development status, advantages, and concerns is shown in Table 4. The energy penalties and total utility raw material costs are shown in Table 5.

Detailed information, including flow sheets, chemical energy balances, information on sulfur versus sulfuric acid production, gasification subsystems, and additional process information, is available in the two-volume final report.

The next step in the regenerable FGD program is currently under way. This step is the detailed design of the most promising processes against specific sites. Proposals have been received and evaluated for 10 processes. Of these, the most promising subloop (Foster Wheeler Energy Corp.'s Resox process) makes elemental sulfur from concentrated SO_2, using coal as a reductant. This evaluation recommended design and construction of Resox as a "back end" to a Bergbau-Forschung char adsorption unit now in operation at a STEAG unit in Lünen, West Germany. This back end, when matched with front-end systems under study, is projected to be economical and relatively uncomplicated. Economic and technical evaluation results will be published in a report prepared for EPRI by the contractor on this project. Stone & Webster Engineering Corp. *Project Managers: Stuart Dalton and Tom Morasky*

Reactor Safety Tour

A meeting of EPRI's Nuclear Safety Task Force at the Idaho National Engineering Laboratory will be of value in EPRI's continuing R&D in reactor safety.

A tour of safety-related facilities taken by EPRI's Nuclear Safety and Analysis Task Force at Idaho Falls, Idaho, may become the model for similar tours.

Each department task force is made up of utility management and engineers who advise EPRI on R&D needs of the utility industry, assess needs, and measure priorities and program values. According to the chairman of the Nuclear Safety and Analysis Task Force, Jack B. Moore, "The task force used this opportunity to obtain a firsthand view of government-supported safety research of potential importance to the utility industry."

The 15 task force members and 7 members of EPRI's staff reviewed the technical programs and experimental facilities operated by EG&G Idaho, Inc., for ERDA's Idaho National Engineering Laboratory (formerly the National Reactor Testing Station). The work is funded by the Nuclear Regulatory Commission.

Major attention was given the power burst facility (PBF), the loss-of-fluid test (LOFT) facility, and a small nonnuclear facility called Semiscale.

As PBF was operating at the time of the task force visit, the group inspected it first, getting a description of the facility, its objectives, and the status of the program. The PBF reactor can be operated at steady-state power up to 28 MW thermal. Sample fuel rods are placed in the water-cooled reactor, which can be operated in a transient mode to simulate abnormal reactor power operation. Without affecting the flow rate in the rest of the core, the flow of coolant water past the sample rod can be adjusted by valves to simulate undercooling effects on the sample rod. The test conditions are directed toward obtaining information about fuel rod behavior for three classes of accidents postulated for LWRs: power-cooling mismatch, loss-of-coolant accident (LOCA), and excess reactivity insertion.

PBF has been in operation for about 18 months and has conducted tests, some with multiple independent fuel rods, at a rate of about one per month. During this operational period, the PBF program has developed very advanced techniques for controlling and monitoring the experimental environment of the test fuel rods. The result of the new techniques is a high usability factor for the PBF experimental data.

The EPRI Fuel Performance Program plans to incorporate appropriate results from this program into the fuel performance data base being created by a research project on fuel rod mechanical performance modeling (RP971).

Test Area North facilities

After a brief stop at the radioactive waste management complex, the group went to Test Area North where LOFT and Semiscale are located. While differing considerably in size and flexibility, both are used to simulate plant behavior in the unlikely event of a LOCA. They are used to provide data for development and verification of PWR safety analysis codes. Through its contractors, EPRI is involved in both pre- and postanalysis of experiments performed at LOFT and at Semiscale. These analyses are contributing directly to EPRI's development of the RELAP and RETRAN plant simulation computer codes for use by the utilities. It is anticipated that the results of this and related work will permit conservatisms built into present safety analysis methods to be quantified, permitting greater reactor operating flexibility at no cost in real safety.

Semiscale, about $1/30$ the size of LOFT in volume, is more flexible and the first of the two to begin operation (1965). Early experiments involved simulation of separate aspects of a LOCA (e.g., expelling coolant from a small simulated reactor vessel by a blowdown nozzle). More recently, more of the plant was simulated, leading to the present configuration, called MOD-1. The MOD-1 system contains $1\frac{1}{2}$ loops, has a 1.68-m (5.5-ft) core, and simulates the LOFT system. More than 40 experiments have been run in Semiscale MOD-1, several as counterparts to planned LOFT experiments.

The LOFT facility is $1/50$ the size of a large commercial PWR. In contrast to Semiscale, which operates with electrically heated rods to simulate core power, LOFT will contain actual nuclear fuel. The initial core will be 1.68 m (5.5 ft) long although the system can accommodate a 3.66-m (12-ft) core. (Plans for MOD-2 in Semiscale are to include 3.66-m heater rods to compare the relative behavior of 1.68-m and 3.66-m cores.)

Experiments in LOFT began in 1976 without nuclear fuel. This first series of tests was used to check out the plant and verify its behavior in isothermal conditions (i.e., no core heat). Nuclear fuel will be loaded in 1977 and experiments run with the core at power in 1978.

Extensive measurements of pressure, temperature, flow rates, void fractions, and so on, are made during each experiment in each of the two facilities. These variables are used for comparison with calculations to verify—or reveal any weakness in—the calculation methods used for safety analysis. It was clear from the presentations that the continuing development and testing of instrumentation used in these facilities is a major portion of the program.

The productiveness of the tour, hosted by W. B. Hannum, deputy manager of the ERDA Idaho Operating Office, suggests that visits to other facilities should be made in the future. "Occasions for the task force to observe directly the safety work in progress enhances our ability to review our program in considerable detail," observes Walter B. Loewenstein, director of EPRI's Nuclear Safety and Analysis Department.

The mobile LOFT reactor shown entering its "home" with the aid of a switching engine. The facility is designed for maximum flexibility in experiments to verify safety.

High-Intensity Ionizer for Improved ESP Performance

by Owen Tassicker and James Schwab

Savings in the size and cost of electrostatic precipitators appear possible with an ionizer that imparts from three to five times higher particle charges in a shorter travel and at faster gas velocities. Resultant improvement in collection efficiency means less collector area is needed for a given control capability.

□ An EPRI technical feature

Owen Tassicker is a project manager in the Air Quality Control Program of EPRI's Fossil Fuel and Advanced Systems Division. James Schwab is senior vice president of Air Pollution Systems, Inc.

A major constraint on the firing of pulverized coal in electric utility boilers is the collection (not to mention disposal) of large quantities of fly ash. Traditionally, this has been the job of the electrostatic precipitator (ESP). However, although a collection efficiency of 95% was formerly satisfactory, some new regulations require an efficiency in excess of 99.5%. At the same time, the shift toward low-sulfur coal generally leads to a low-conductivity ash that seriously interferes with precipitator performance. As a result, precipitators have become large and expensive, with efficiencies that are difficult to predict accurately. Also, reliability is not as high as formerly, simply because of the large number of wires, plates, and rappers.

EPRI has examined several technological improvements or alternatives to the ESP in a search for a fine-particle removal apparatus with high efficiency and low energy consumption. This screening has narrowed to three technologies—improved conventional ESPs, fabric filtration, and advanced ESPs. An advanced dry ESP technology involving a high-intensity ionizer developed by Air Pollution Systems, Inc., (APS) is examined in this discussion.

Impact of particle emission standards

During recent years the permitted emission of solid particulate has been gradually reduced to the current federal standard of 43 g/10^9 J (0.1 lb/10^6 Btu), indicating the direct relation between allowable emissions and the amount of electric power generated. In a typical case this emission standard corresponds to 60 mg/m^3 (0.024 gr/ft^3) and requires that about 99.5% of the fly ash be collected before discharge from the stack. Since the size of an ESP is determined by the efficiency of fly ash collection required, an increase in required fly ash collection efficiency requires a corresponding increase in equipment size and cost.

Current federal standards for the emission of sulfur dioxide gas from coal-fired power stations allow 515 g/10^9 J (1.2 lb/10^6 Btu). For an average coal with a heat value of 23 × 10^6 J/kg (1 × 10^4 Btu/lb), the permitted maximum combustible sulfur content in the fuel is thus ~ 0.6%. Coal with lower sulfur content, used to minimize sulfur dioxide emissions, generally yields highly resistive dust. Because the size of the precipitator also increases with increasing electrical resistivity of the fly ash (*1*), the use of low-sulfur coal further increases the size and cost of the precipitator.

This resistivity problem has been avoided in some cases by using conditioning agents (*2–4*) or operating the precipitator at the economizer outlet (hot-side precipitator) (*5*). These solutions are not as universally attractive as previously expected (*6*). Some ashes do not respond to conditioning agents. Other ashes still have resistivity problems under hot-side conditions, especially under light load when the precipitator temperatures may be reduced.

Separate ESP stages

Two-stage electrostatic precipitation has always been attractive in theory as a means of optimizing the use of electrostatic forces in the collection of fine particles. Devices built on this principle, such as room ventilation ESPs, ionize the gas and charge the particles in one stage, then collect the particles and dispose of them in a second stage. Until the present time, two-stage precipitation has not proved practical at the vast gas volumes treated in the electric power utility industry, where 1000 MW leads to a flue gas flow of about 1400 m^3/s (3 × 10^6 ft^3/min).

Considerable insight into the operation and limitations of conventional precipitators is provided by reference to precipitator theory summarized below.

A version of an advanced electrostatic precipitator embodying two-stage principles is shown in Figure 1, where a high-intensity ionizer precedes three conventional collector fields.

Precipitator theory

For either single-stage or two-stage precipitation, the modified Deutsch-Anderson equation represents the behavior fairly well (*7, 8*):

$$\eta = 1 - \epsilon^{-(\omega_k A/Q)^b} \qquad (1)$$

where
- η = collection efficiency of precipitator
- ω_k = mean particle migration velocity, m/s
- A = total collecting plate area, m^2
- Q = gas volume flow rate, m^3/s
- $b \simeq 0.5$, accounting for dispersion of particle size, nonuniformity in gas flow, and so on

A simple dynamic analysis of the motion of a single charged particle (> 1 μm) in an electric field subject to Stoke-Cunningham viscous drag results in the following informative equation of its ideal migration velocity:

$$\omega = p\frac{\epsilon_0 E_c E_p r}{\mu} \qquad (2)$$

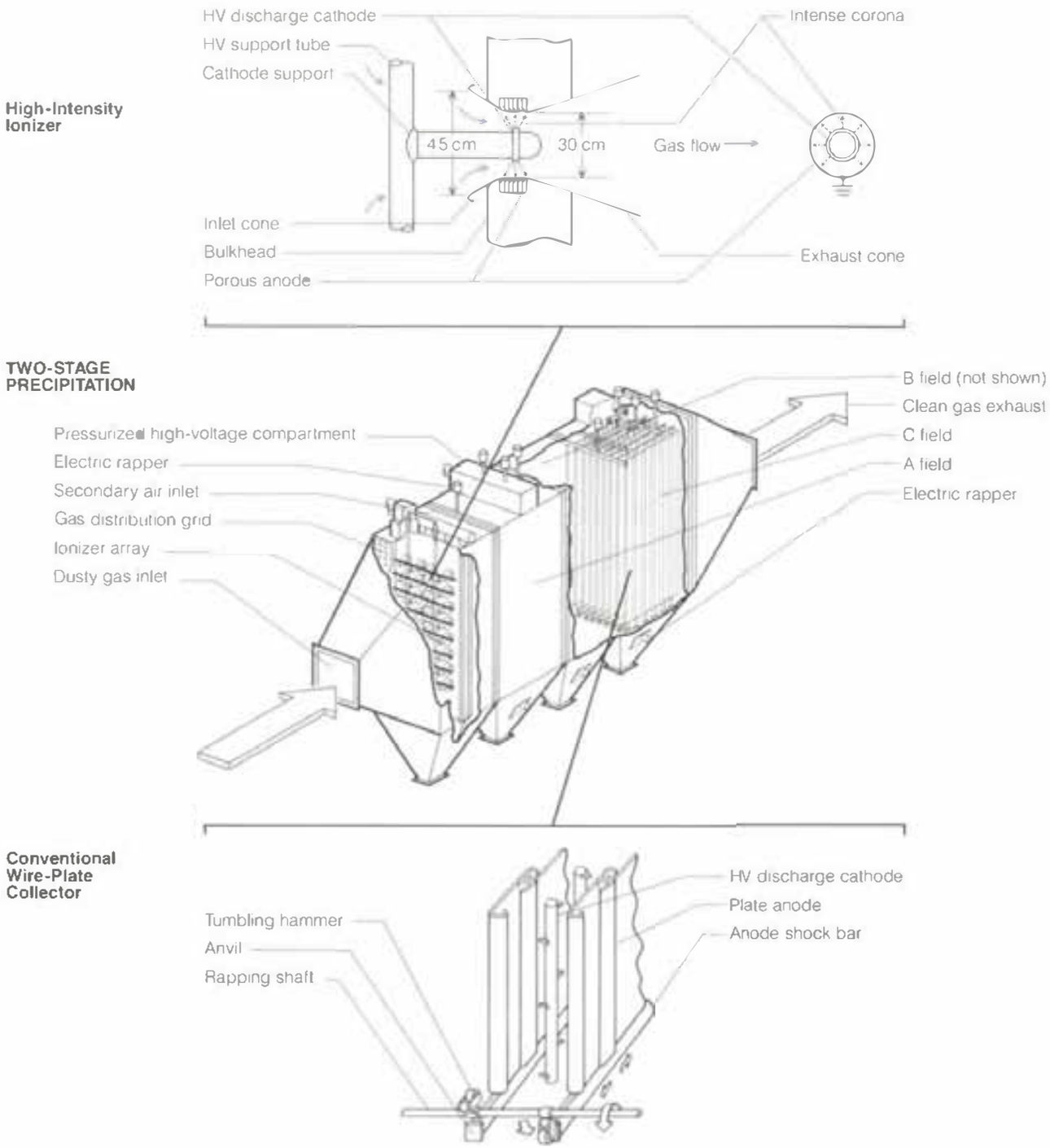


Figure 1 **Two-stage precipitation.** A high-intensity ionizer precedes three conventional collector fields. Flue gas from the air preheater approaches the ionizer array at 2–3 m/s (6.5–10 ft/s). The array acts as a diffuser plate, with each perforation containing an intense corona discharge in which gas is treated at about 25 m/s (80 ft/s). The highly charged dust enters the collecting fields at 1–2 m/s (3–6 ft/s). **High-intensity ionizer.** Each element comprises a cathode disc concentrically contained within an anode venturi throat. The ionizer array is a matrix of many such elements. As gas passes through the radial corona, most of the flow energy is recovered, since $\Delta P \simeq \frac{1}{4}$ in H_2O. The electric field across the gap is nearly constant at 10–20 kV/cm. The ratio of cathode to throat area is about 0.2. **Conventional wire-plate collector.** Corona discharge emanates from the HV electrodes, traverses the interelectrode gap, and reaches the collecting electrodes. Charged dust migrates to the collecting electrodes, from which it is dislodged (into hoppers below) by regular blows from the rapping mechanism.

where ω = ideal terminal particle migration velocity toward the collecting surface, m/s
$\epsilon_0 = 8.854 \times 10^{-12}$ (permittivity of free space)
p = constant depending on the dielectric constant of the particle ($\simeq 1.5$ for fly ash)
E_o = charging electric field, V/m
E_p = precipitating electric field, V/m
r = particle radius, m
μ = host gas viscosity modified by the Cunningham correction factor, kg/ms

The equation is modified for submicron particles where diffusion charging dominates (*1, 9*), charge on the particle increasing with ion density N_o in the charging zone.

A great deal may be inferred about precipitator operation from these equations.

- Clearly, the higher the effective particle migration velocity ω or the larger the specific collecting area A/Q, the higher the efficiency will be.

- The migration velocity ω of a single particle is proportional to particle radius—confirming the common experience that large particles are more easily collected.

- More important in this context, a higher charging electric field E_o or precipitating electric field E_p leads immediately to enhanced migration velocity and efficiency.

In a conventional single-stage precipitator, E_o and E_p become the same, so that

$$E_{av} = E_o = E_p = V_a/\ell \qquad (3)$$

where V_a = applied voltage
ℓ = wire-plate spacing

When a layer of resistive material is deposited on the collecting or charging electrodes, there is a voltage gradient, E_f, across it due to the corona current flow given by

$$E_f = J_o \rho \qquad (4)$$

where E_f = voltage gradient in dust layer, V/m
J_o = corona current flux density on collector plate, A/m²
ρ = electrical resistivity of deposited fly ash, Ω•m

If this voltage gradient exceeds 12–20 kV/cm, the dust layer breaks down, and the damaging phenomenon of back ionization sets in.

Optimizing performance

It is clear from Eq. 1 that for a given gas flow rate Q, the required collector plate area (and the cost of the precipitator) depends directly on the mean particle migration velocity ω_k toward the collector surface. Anything that can be done to increase ω_k will enhance the collection efficiency. From Eq. 2, increasing the average charging field E_o or the precipitating field E_p are two such opportunities.

Therefore, by whatever means the applied voltage across the electrode gap can be increased (Eq. 3), enhanced average migration velocity and efficiency result. However, to meet today's stringent emission standards, an extended plate area, A, of the conventional precipitator must be provided in order to collect both the required fine and the coarse particles. This is accomplished generally by increasing the precipitator size (length) in the direction of gas flow.

The high-resistivity ash often associated with western coals causes deterioration in both the charging and the collection processes. When the breakdown field is reached in the ash layer as described in Eq. 4, the formerly passive layer of ash erupts into hundreds of tiny glowing needle points. These emit positive ions into the gas space that previously contained only negative ions. Voltage that can be sustained drops dramatically, excessive sparking sets in, and collection efficiency deteriorates. While some electric field E_f is needed to provide a holding force to retain the dust on the plates, it should be kept below the threshold of back corona. Typically, this occurs when the ash resistivity is about 2×10^8 Ω•m.

As a remedy for this situation, corona current flux density J_o must be reduced in accordance with Eq. 4. Unfortunately, corona current density can only be reduced by reducing the applied voltage V_a, since the two are implicitly linked by the corona V–I characteristic, a typical example of which is shown in Figure 2 (wire-cylinder geometry). Hence, reducing the voltage gradient in the dust layer to avoid excessive back corona can be accomplished only by reducing both the charging field and the precipitating field E_{av} to a value of from 4–5 kV/cm for low-resistivity ash to around 3 kV/cm for high-resistivity ash. The resultant loss of migration velocity implicit in Eq. 2 (where substitution gives a field strength term of E_{av}^2) can only be compensated, in accordance with Eq. 1, by increasing plate area.

Ideal two-stage precipitation

The limitation of the conventional electrostatic precipitator has always been that it has not been possible to separate and optimize the charging and collection processes. Two-stage precipitation has always offered the possibility of attaining this separation.

Such a two-stage device depends for its success on several criteria:

- The electric charging zone operates at a much higher field strength E_o and ion density N_o than is presently achieved.

- The electric charger will handle boiler flue gas streams of 1400 m³/s (3×10^6 ft³/min), the scale of a 1000-MW power plant, from electrical, mechanical, structural, and aerodynamic viewpoints, and with the degree of reliability expected in the utility industry.

- The charging zone can be immunized and cleaned of unwanted, parasitic deposition of fly ash.

- High gas velocities can be accommodated so that the device is physically small.

- The cost of the overall system of charger followed by a matched conventional collector must be less than that of a traditional precipitator.

Whereas earlier efforts at two-stage precipitation were successful in meeting some of these criteria (*10*), none appears to have been capable of meeting them all.

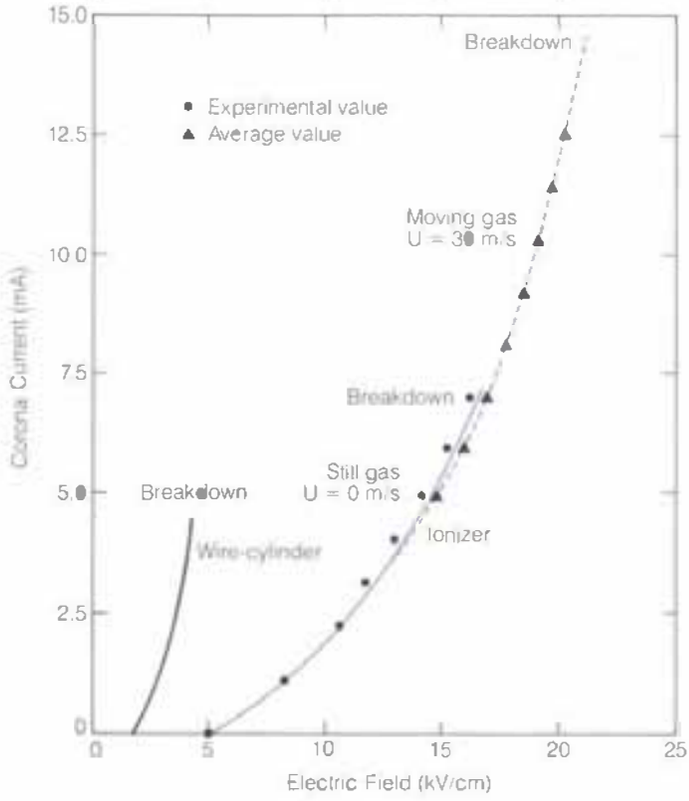
High-intensity ionizer

APS has developed a new electrode geometry (Figure 1) that promises to meet all the above criteria. An intense, highly stable corona—expanding both radially and axially—is established in the gap between the cathode disc and the venturi anode. The axial length of the corona on the venturi boundary is quite small (about 10 cm) since it is contracted by field-focusing electrodes. Average electric fields across the gap of 12–24 kV/cm have been achieved, depending on the gas temperature and velocity and the type of ash loading in the gap. Such fields lead to particle charges 3–5 times higher than those obtained in present precipitation practice. The unique nature of the discharge depends on the correct choice of disc-to-anode spacing, following which the corona expands in a three-dimensional fashion.

Special measures to keep the anode clean and to deal with highly resistive ash are now possible because parasitic deposition of dust occurs only in a 10-cm or so length of anode. In conventional geometries, such as wire-cylinder or wire-plate, it is not possible to maintain clean anodes immunized against highly resistive ash because of the large surface areas.

Whereas anodes of from 15 cm to 40 cm diam have been built and tested, the optimal commercial size appears to be around 30 cm diam. With an HV busbar assembly to energize them, an array of such ionizers can be

Figure 2 Corona V–I characteristics: comparison of the high-intensity ionizer and conventional wire-cylinder geometry is startling. In a moving gas, the average electric field in the ionizer is four times higher. Ambient laboratory air test conditions: wire diam 0.3 cm, cylinder diam 30 cm; ionizer anode diam 30 cm, length 12 cm; cathode diam 9.8 cm.



built as indicated in Figure 1, resembling a diffuser plate commonly used for the correction of gas flow. The device is capable of expansion to any gas flow by increasing the number of ionizers in the array. Since an individual ionizer is compact and solidly built, the array is a rigid mechanical structure.

As gas velocity in the corona zone is as high as 30 m/s (100 ft/s) (in contrast to conventional precipitator gas flow of around 2–3 m/s), the APS high-intensity ionizer is physically very compact.

Corona and gas-dynamic effect

Since efficient operation of the ionizer and the collector stages depends on the electric fields E_o and E_p, it is important to examine the V–I corona characteristics that determine them. V–I corona data for a conventional wire-cylinder and a high-intensity ionizer are shown in Figure 2. The average field strength that can be established across the gap in the wire-cylinder before breakdown is around 5 kV/cm in either a still or a moving gas. While a field E_o of 16 kV/cm may be sustained in the case of the ionizer in still gas, it is seen that at a typical gas velocity of 30 m/s in the charging zone, the field rises to 22 kV/cm. Using ambient air at this velocity, field strengths of 24 kV/cm have been regularly produced in the APS ionizer geometry. This may be regarded as the upper limit because even for idealized flat plates separated by 10 cm in ambient air the sparkover gradient is 25 kV/cm.

The improved stability and intensity of the corona under high transverse gas velocities is due to the movement of the ion space-charge cloud and the dissolution of the streamers that precede breakdown.

Proposed installations incorporating an ionizer are being conservatively designed today with charging fields E_o of 12 kV/cm. But because techniques for immunizing the anode from the effects of high-resistivity ash are so rapidly being developed, the ultimate goal for the ionizer technology is for an E_o of 20 kV/cm.

At present, for two-stage precipitation incorporating a high-intensity ionizer and treating high-resistivity fly ash, the values placed in Eq. 2 are $E_oE_p = 12 \times 3$. For a conventional precipitator, $E_oE_p = 3 \times 3$.

The ion density N_o in the gap, which enhances the charging of fine particles, is greater by a factor of 100 for the high-intensity ionizer.

Particle charging

Particle-charging efficiency has been studied with respect to gas velocity (residence time). Implicit in Eq. 2 is the classical charging theory of Pauthenier, extended by others (*1, 9*), so it is important to be able to compare the measured and calculated values of saturation charge. Figure 3 illustrates the gas velocity effect on charging of fine particulate. Charge-to-mass measurements were made at gas velocities up to 40 m/s (130 ft/s) and field strengths up to 16 kV/cm. These data show that at 30 m/s (100 ft/s) the actual charge on a particle is equal to the theoretical calculated saturation charge in a still gas. At gas velocities less than 30 m/s, the charge on a particle would be even higher than classical field-charging theory would indicate.

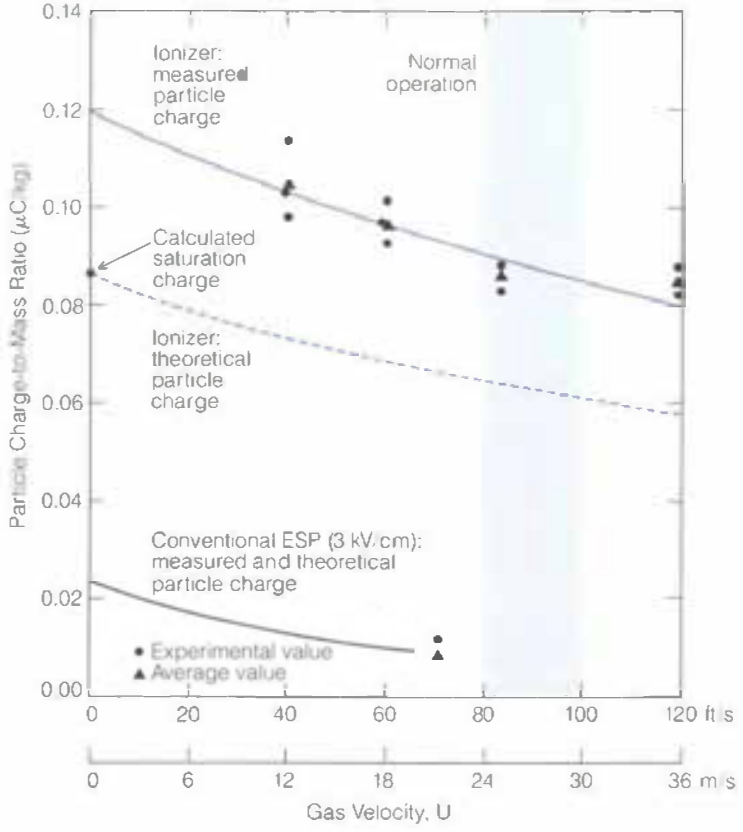
Thus, in addition to being able to sustain much higher electric fields than other geometries, the high-intensity ionizer actually imparts charges by these fields that are some 40% higher than any theory would predict. This beneficial anomaly is attributed to a free electron charging effect (*11*) created by the high field in the high-intensity ionizer.

Anode development

A primary advantage of the high-intensity ionizer is the relatively small anode (ground) surface ($\simeq$0.08 m² per m³/s or $\simeq$0.4 ft² per 10^3 ft³/min) that must be maintained in an ash-free condition. The dry charging stage must be protected against the phenomena of back corona and excessive sparking problems associated with parasitic deposition of high-resistivity ash, even though the high gas velocity in the venturi throat tends to be self-cleaning.

The most successful development to date

Figure 3 Particle charging efficiency: actual charges imparted to particles by the high-intensity ionizer are compared with the maximum (steady-state saturation) charge calculated by classical theory. At zero gas velocity, the measured charge is 40% higher than the theoretical. With reduced residence time, charges decreases as expected. At 28 m/s (90 ft/s), measured charge equals theoretical steady state. Charging in a conventional ESP treating high-resistivity ash is shown for comparison. Particles: TiO_2 dust (mass mean diam 0.5 μm); E_{av} = 11.6 kV/cm; I = 1 mA; anode diam = 15 cm.



has been the porous or gas-swept anode, of which various mechanical configurations have been built and tested. It is kept relatively free of fly ash (and back corona) for long periods by a small flow of clean gas (~6% of the gas stream). Its present construction consists of a series of spaced discs, each of which has an inner lip guiding the bleed gas parallel to gas flow, so establishing a boundary layer.

Heated anodes (above 315°C, 600°F) reduce ash resistivity at the surface so that no back corona develops. Steps are being taken to investigate reducing the energy consumed in heating the anodes.

Cooled anodes (65–120°C, 150–250°F), which consume less energy than heated anodes, are also under development. Laboratory and field pilot tests of the porous anode that employed cooling through the injection of gas at 20–70°C (70–160°F) have been conducted.

An anode with a thinly deposited semiconductor coating has shown no detrimental back corona with high-resistivity fly ash deposits up to 5 mm thick. The maximum current density in laboratory tests has been 10 μA/cm²—100 to 1000 times higher than that found in conventional precipitators. Promising candidate materials with high puncture resistance are being evaluated for further laboratory and field testing.

Field pilot test program

Field testing of the high-intensity ionizer was conducted at the John Sevier steam plant of the Tennessee Valley Authority (TVA), under the auspices of the TVA Power Research staff, EPRI, and APS. An array comprising two 23-cm (9-in) diam ionizers was attached directly to the inlet face of a standard three-field pilot ESP of Svenska Fläktfabriken design. A gas sidestream with an isokinetic extractor of 1.6 m³/s (3500 ft³/min) capacity was installed between the multiclones and the station precipitators on boiler No. 2. The results of three months of full-time and two months of part-time testing disclosed:

- Particle penetration through the collectors was reduced by 70–80% with the ionizer energized when treating highly resistive ash. To gain maximum benefit from the system, the collecting fields must be matched to the ionizer stage; this could not be done on the tests at the John Sevier plant.
- The ionizer maintained excellent electrical, mechanical, and structural stability and there was no detectable erosion.
- No new gaseous species were detected at the outlet as a result of the high-intensity corona.
- The ionizer performed equally well on run-of-the-station coal (S = 1.7–2.5%) and on Haddocks coal (S ≃ 0.8%)
- On the low-sulfur coal, average fields E_a = 10.8 kV/cm with a current flux on the anode of J_o = 6.33 μA/cm² were sustained for long periods of time. By contrast, in the conventional collector stage following, the corresponding values were 3.3 kV/cm and 0.013 μA/cm², respectively.

The tests at TVA are sufficiently encouraging to warrant larger scale tests from which firm design criteria and cost-benefit analyses will be derived.

Prototype testing at Arapahoe

Given the successful laboratory and field pilot tests to date, confirmation of the commercial potential of the ionizer must be based on completion of an orderly development program (*12*) planned at the EPRI Advanced Particulate Control Facility in Denver. Of particular importance will be the prototype-scale 16.5-m³/s (35 × 10³ ft³/min) tests comprising a 3 × 5 array of 25-cm-diam ionizers (*13*) followed by collector stages, which (though essentially conventional) will be matched to the ionizer array to take full advantage of the precharging (*14*). This will entail fitting the collector stages with

larger-than-normal discharge electrodes and operating with current densities $J_o < 0.02\ \mu A/cm^2$.

The slipstream will be taken from the No. 4 boiler of the Arapahoe Power Station of the Public Service Company of Colorado, which normally fires Energy coals with a sulfur content of 0.74% and an ash content of 14% (which is in the medium-high resistivity range of 10^9–$10^{10}\ \Omega$·m). Design criteria for eastern-type coals will be derived by sulfur trioxide conditioning of the flue gas.

To secure rapid commercialization, the high-intensity ionizer is being given high priority in the testing program during 1977.

Commercialization and cost benefits

There are two possible uses of the high-intensity ionizer: as a retrofit to existing installations that do not comply with emission standards and in new installations (*15*).

In retrofits, a slice would be made in the duct upstream of the existing precipitator and the ionizer array slipped into position. While costs vary from site to site, current cost estimates prepared for a 142-m^3/s (3×10^5 ft^3/min) gas passage retrofit for TVA are around $4750 per m^3/s ($2.25 per ft^3/min) installed. This represents a cost saving of some 30–60% compared with a conventional ESP retrofit, with considerably less plant space occupied.

In a new installation, savings gained by the use of the high-intensity ionizer (based on observed laboratory migration velocities) are expected to be in the order of 30%, with no energy penalties incurred.

During the coming tests at Arapahoe, both the cost-benefits and firm design criteria for full-scale installations will be determined.

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Acknowledgment

Professor Emeritus Leonard B. Loeb (University of California at Berkeley) and Dr. Wayne Sproull provided technical review and counsel during the ionizer development. Kaiser Engineers and Enviro-Energy performed technoeconomic analyses.

New Technical Reports

ELECTRICAL SYSTEMS

Proceedings of an Engineering Foundation Conference. Power System Planning and Operations: Future Problems and Research Needs

EL-377-SR Special Report

In August 1975 a conference on the state of the art of power system planning and operations was held at New England College in Henniker, New Hampshire. The format of this conference was so successful that it was used again for the Henniker Conference held August 22–27, 1976.

The 1976 conference was sponsored by the EPRI System Planning, Security, and Control Task Force with the endorsement and cooperation of ERDA and under the auspices of the Engineering Foundation. James L. Davidson of the Long Island Lighting Company served as general conference chairman.

The themes of the planning sessions were: overview of planning practices, impact of load management on planning, current generation and transmission planning methodologies, load forecasting, and system reliability. The themes of the operations sessions were: problems in power system operations, control and security considerations, research needs for operations, and coordination of planning and operations. The sessions covered domestic and foreign practices as well as planning and operations for small utilities, large utilities, pools, and regional councils.

This report includes the papers presented at the 1976 conference, together with edited summaries of the panel discussions.

Research and Development on DC Circuit Breakers

EL-379 Final Report (RP91)

This report describes development of a laboratory prototype of an HVDC circuit breaker. Testing of this prototype was carried out on the Pacific NW-SW DC Intertie rearranged to represent a three-terminal system. The fundamental difference from previous breaker configuration concepts was the partitioning into separate devices of the following breaker functions: carrying the continuous current, interrupting fault or load current, and absorbing energy. This power system device is capable of interrupting over 1000 A against 100 kV. It features an in-line mechanical switch capable of full opening (1 in) in 1.6 ms. *Hughes Research Laboratories*

Development of a Current Limiter Using Vacuum Arc Current Commutation Phase I: A Feasibility Study for Using Arc Instability in Vacuum for Current Limitation

EL-393 Final Report (RP564-1)

Electric utilities have stated a need for fast-acting, current-limiting devices, which insert impedance into power circuits. Impedance insertion during the initial rise of fault current reduces the fault current peak and simplifies interruption requirements of conventional circuit breakers. Reduction of the fault current peak also reduces electromagnetic forces, which would otherwise damage circuit components.

This report documents progress in Phase I of this program, an investigation of forced instability of vacuum arcs to insert an impedance during fault current rise. A transverse magnetic field proved to be an effective and attractive method for causing current commutation into a current limiting resistor. The interaction of vacuum arcs with applied transverse fields has been analyzed theoretically and experimentally. Experiments were also performed to investigate the current commutation ability of sealed vacuum devices. In addition, the program involved development of high-speed repulsion coil actuators, analysis of circuit transients associated with current limiters, and design of magnetic-field-coils and their associated power supplies. *Westinghouse Electric Corp.*

ENERGY ANALYSIS AND ENVIRONMENT

User's Guide to the Data Tapes From EPRI Projects

EA-235 Final Report (Vol. III) (RP431)

This volume provides a user's guide to the three data tapes from RP431 reported in volumes I and II. The primary purpose of the guide is to assist those interested in conducting analyses using the data, and as such it is not required material for those interested only in the RP431 analysis. The tapes contain the data reported and analyzed in the first two volumes, as well as the disaggregate data on which those estimates were based. In many cases, the procedures for constructing the data are also on the tapes. In general, these data consist of state appliance stock estimates and declining block rate structure data series. *Data Resources, Inc.*

Proceedings of the Workshop on the Measure of Intangible Environmental Impacts

EA-405-SR Special Report

An understanding of comparative environmental impacts associated with alternative technologies or geographic sites is needed for rational decision making, and EPRI's Environmental Assessment Department is directing a sizable research program to achieve this end. Another category of effects has aroused public interest and must also be considered. These intangible effects, such as esthetic impacts, visibility reduction, and low-level noise, are less easily specified or quantified.

This report presents information generated at a workshop on the measurement of intangible environmental impacts. One purpose of the workshop was to learn the state of the art on the measurement of these impacts so that they can be considered properly in the future. A second objective was to define specific research topics that EPRI might pursue to improve existing techniques for quantifying intangible impacts. The methodological approaches considered were the hedonic approach, decision analysis approaches, approaches based on observations of individual behavior, bidding game and asking approaches, and approaches that combine social and technical factors. *Sigma Research, Inc.*

FOSSIL FUEL AND ADVANCED SYSTEMS

Technical and Economic Assessment of Phase Change and Thermochemical Advanced Thermal Energy Storage (TES) Systems

EM-256 Final Report (4 Vols.) (RP788-1)

In December 1974 EPRI initiated research on high-temperature, gas-cooled central receivers for solar energy. In February 1976 an EPRI–ERDA program coordination was initiated to examine in greater detail the technical feasibility of higher-temperature thermal energy storage (TES). The two advanced systems are a phase-change energy storage with inorganic salts and a reversible thermochemical-reaction energy storage system. A third system, a sensible-heat, pebble-bed energy storage system, was investigated as a near-term benchmark.

The report on the information developed through June 1976 is presented in Volume I of this document. Volume II describes the computer program used in conceptual studies of phase-change thermal energy storage systems. Volume III describes the computer program used to size and evaluate the SO_2/SO_3 thermochemical energy storage device for application with the high-temperature, gas-cooled solar power plant. Volume IV describes the computer program used to simulate the operation of the high-temperature, gas-cooled solar power plant.

The results of the second part of the research program will be reported in November 1977 in an ERDA technical report. An interim summary report, available from EPRI, provides an overview of the study. *Boeing Engineering and Construction*

A Technoeconomic Analysis of Large-Scale Thermochemical Production of Hydrogen

EM-287 Final Report (RP467)

This report presents capital and operating costs and overall process efficiency for a four-reaction thermochemical process, which produces hydrogen from water. These results were obtained from a detailed preliminary plant design made after the selection of a suitable process and the establishment of a design basis.

Process selection involved the evaluation of estimated process efficiency, materials problems, and availability of data for known thermochemical cycles. This initial screening resulted in the identification of four cycles, which appear promising in terms of cost and efficient hydrogen production. A detailed analysis of these four cycles involved the preparation of mass and energy balances, including the interface with the nuclear heat source and the specification of separation techniques and operating conditions. Process

thermal efficiency was reestimated and the problems involved in the design of a large-scale plant were evaluated in more detail. A four-step methanol process was selected for the detailed plant design, cost estimation, and efficiency analysis. *University of Kentucky and Combustion Engineering*

Doublet Fusion Experimental Power Reactor Conceptual Design Study

ER-289-SY Summary Report (Vol. IV) (RP323-1)

The nuclear fusion process can provide all of our society's energy needs in the twenty-first century. Because of the large, long-range efforts required for success, most research is supported by government agencies, primarily ERDA. However, in order to evaluate progress and involve the utility industry in early development, EPRI supports research and development efforts in fusion to assure a user viewpoint.

This document reports the results of a study of an experimental fusion power reactor. It attempts to present the salient features of a possible future device, which may be constructed to bridge the gap between present research and the ultimate commercial fusion power plant. *General Atomic Co.*

Guidelines for the Design of Mist Eliminators for Lime/ Limestone Scrubbing Systems

FP-327 Final Report (RP209)

This report presents the current state of the art of mist eliminator design for lime and limestone flue gas desulfurization (FGD) scrubbing systems. Chevron and baffle-type mist eliminators were treated extensively while radial vane, radial baffle, and electrostatic precipitator mist eliminators were covered to a lesser degree. Background information covered collection, reentrainment, and mist eliminator failure mechanisms. Design factors affecting the performance, cost, and collection efficiency (such as mist eliminator construction, configuration, and wash systems) were also presented. Extensive tables summarize: scrubber background information, mist eliminator design specifications, and mist eliminator wash system specifications, for all operational lime and limestone FGD systems in the United States. *Battelle, Columbus Laboratories*

Conference Proceedings: Low Activation Materials Assessment for Fusion Reactors

ER-328-SR Special Report

This conference examined the case of a low-activity fusion reactor. Possibilities for hands-on maintenance were judged to be increased substantially for a low-activity design. The resultant reduction in maintenance time and improvement in plant availability were identified as the greatest potential payoff for a low-activity reactor. Considerable differences of opinion were expressed about the location within the reactor core where hands-on maintenance may be possible. Other potential advantages discussed were siting, accident downtime, public acceptance, and transportation/storage of activated components. Material choices discussed for low-activity, first-wall/blanket structure were limited to aluminum, vanadium, titanium, silicon carbide, and graphite. *McDonnell Douglas Astronautics Co.*

EPRI Asilomar Papers on the Possibility of Advanced Fuel Fusion Reactors, Fusion-Fission Hybrid Breeders, Small Fusion Power Reactors

ER-378-SR Special Report

In December 1976 an EPRI ad hoc advisory panel met at Asilomar, California, for a three-day general discussion of topics of particular interest to utility representatives. The three main topics considered were: the possibility of advanced fuel fusion reactors, fusion-fission hybrid breeders, and small fusion power reactors. This report describes the ideas that evolved at that meeting.

An example of a neutronless fusion reactor using the p-^{11}B fuel cycle is described along with the critical questions that need to be addressed. The importance to the utility industry of using fusion neutrons to breed fission fuel for LWRs is outlined, and directions for future EPRI research on fusion-fission systems are recommended. The desirability of small fusion power reactors to enable the early commercialization of fusion and for satisfying users' needs is discussed, and areas for possible EPRI research to help achieve this goal are presented.

Application of the Alsthom/Exxon Alkaline Fuel Cell System to Utility Power Generation

EM-384 Final Report (RP584-1)

Exxon Enterprises Inc. has completed an evaluation of Alsthom/Exxon alkaline fuel cell technology for application to utility power generation. The purpose of this study was to determine how close the technology could come to EPRI efficiency, investment, and related targets and to begin to define limitations yet to be overcome. A systems analysis was conducted to explore the effect of variables, such as fuel cell operating temperature, fuel type, and degree of carbon oxides preremoval on efficiency and cost. Most of the effort centered on minimizing cost and heat rate by selecting appropriate process techniques and heat-integrating various parts of the process.

Two routes were found for meeting the EPRI heat rate targets: 7100 Btu/kWh with methanol, and 7500 Btu/kWh with naphtha as starting fuel. The simplest route involved reforming followed by pressure swing absorption, yielding a nearly pure hydrogen feed to the fuel cell. Use of carbonate scrubbing required an increased fuel cell temperature of 393°K; thus waste heat could be used for carbonate regeneration. Investments for a 400-MW plant were between 20 and 30% higher than the target of $200/kW in 1974 dollars. Since the estimates contain no allowance for contingencies, it would be unrealistic to project lower costs. *Exxon Enterprises, Inc.*

Solar-Thermal Conversion to Electricity Utilizing a Central-Receiver, Open-Cycle Gas Turbine Design

ER-387-SY Summary Report (RP475-1)

This report presents a completed conceptual design of a solar electric power plant intended for intermediate load range utility application. This effort encompassed all principal aspects of the plant system, with particular attention directed toward the crucial heliostat field, high-temperature solar receiver, and turbine-receiver interface elements.

The plant design incorporates as the prime mover a conventional and commercially available open-cycle, regenerative gas turbine. A high-temperature ceramic heat exchanger is used to capture concentrated solar radiation and to heat air to the high temperatures required for efficient turbine operation. The generator unit and the solar receiver—heat exchanger are both located atop a steel-reinforced concrete tower surrounded by sun-tracking, reflecting surfaces (heliostats). Costs are estimated lower than those for a water steam solar electric system, while efficiency appears to be superior. *Black & Veatch*

Considerations on a Tritium-reprocessing System Using Solid Tritium Getters in a Lithium-cooled Thermonuclear Reactor

ER-388 Topical Report (RP236-1)

This publication reports the investigation of a tritium-reprocessing system using a solid tritium getter in the lithium-cooled controlled thermonuclear reactor (CTR). Kinetic considerations of the solid tritium getter are examined in detail with particular emphasis on the yttrium metal. Since the startup tritium inventory is known to depend significantly on tritium-reprocessing time, a dynamic model of this system is used to determine tritium transfer rate and associated tritium inventory. Properties and behaviors of aging yttrium tritide were studied to determine the effects of prolonged use of this metal. Considerations of imperfect drainage of lithium and consequent formation of lithium tritide were considered during the reprocessing stage. Since the impurity coatings of stable yttrium compounds, especially the oxide coating, may impede the transfer rate, numerous metal impurity getters were selected for simultaneous removal of impurities in lithium. *University of California, Los Angeles*

Effect of Smoke and Corrosion Suppressant Additives on Particulate and Gaseous Emissions From a Utility Gas Turbine

FP-398 Final Report (RP462-1)

The objective of this program was to totally characterize the effects of smoke and corrosion suppressant additives on the solid and gaseous emissions from a utility gas turbine representative of current combustor design. Selected concentrations of three different smoke suppressant additives were investigated. Representative exhaust samples were extracted from the gas turbine stack and analyzed for total particulate mass loading and composition, particle size distribution, size and chemical state of the emissions derived from the additive base element, polycyclic organic matter, and gaseous emissions including NO, NO_2, CO, O_2, unburned hydrocarbons, SO_2, and SO_3. Tests were conducted at both industrial baseload (nominally 20 MW) and an intermediate load of 15 MW. *KVB, Inc.*

Lead-Acid Batteries for Utility Application: Workshop II

EM-399-SR Special Report

The second lead-acid battery workshop capped two years of studies directed toward providing information that would allow a determination of the viability of today's lead-acid battery for utility application. Cost, technical specifications, and performance of lead-acid battery peaking plants have been reviewed. However, information about market or affordable costs and cost credits is not yet available. An extensive survey of the electric

utility industry is planned, including: a letter to utility executives soliciting interest in a demonstration plant, and a detailed survey of utility planners regarding the elements involved in specific system expansion studies that impact upon the competitiveness of lead-acid batteries.

It is anticipated that inputs from these surveys will be completed by early 1977. EPRI, ERDA, and utility advisers will review the results and decide on EPRI participation in a demonstration plant. If the results are positive, an RFP (request for proposal) will be sent to interested utilities.

Continuous High-Pressure Lump-Coal Feeder Design Study

AF-410 Final Report (RP526)

The purpose of this project was to develop a continuous lump-coal dry feeder for a pressurized fluidized-bed combustor. The approach was to adapt the commercially available Fuller-Kinyon pump to feed coal against a pressure differential of 100 psi or more. The pump was modified and tests were performed at various pressure differentials, with differently pitched screws, two screw rotational speeds, and various seal lengths and configurations. Although the results of this project are not conclusive, test data and observations indicated to the contractor that higher-pressure differentials could be attained by further modifications of the test setup. *Garrett, Inc.*

NUCLEAR POWER

Human Factors Review of Nuclear Power Plant Control Room Design

NP-309 Final Report (RP501)

The Reactor Safety Study, WASH-1400, criticized the design of controls and displays and their arrangements on operator panels in nuclear power plants as deviating from human engineering standards generally accepted in other industries and specified for the design of man-machine systems. The EPRI Task Force for Nuclear Engineering and Operations expressed similar criticism and suggested EPRI retain an organization to review the human factors aspects of the control rooms of nuclear power plants that have recently become operational. Human factors engineering is an interdisciplinary specialty concerned with influencing the design of equipment systems, facilities, and operational environments to promote safe, efficient, and reliable operator performance.

The review covered five representative nuclear power plant control rooms. Methods included a checklist-guided observation system, structured interviews with operators and trainers, direct observations of operator behavior, task analyses and procedure evaluation, and historical error analyses.

The human factors aspects of design practices are illustrated in this final report, and many improvements in current practices are suggested. Current nuclear practices are evaluated in the light of knowledge developed in other industries, and the significance of the differences is estimated in terms of their potential effects on reactor safety and plant reliability. The review also covered the training simulators corresponding to the selected power plants. *Lockheed Missiles & Space Company, Inc.*

Modeling and Estimating System Availability

NP-326-SR Special Report

The need to assure safe and reliable operation of a nuclear power generation station has resulted in the redundant introduction of many systems, subsystems, and components. This redundancy is expected to increase power plant availability. However, estimates of the effectiveness of a potential modification are also necessary. Such effectiveness can itself be measured in terms of system or subsystem availability. Thus, availability is an important statistic for measuring cost-effectiveness.

This report reviews several models that directly consider the random nature of malfunction and repair. Its principal purpose is to show how estimates of system availability may be constructed from component data and how the statistical stability of these estimates may be assessed directly from the data. Illustrations are for small systems of components, but generalization to larger systems is implicit.

This report is basically mathematical in nature but not so much so that the dedicated engineer cannot make use of it. The procedure of securing good estimates of availability from sparse data may be particularly useful.

Field Ionization for Laser Isotopic Separation

NP-334 Final Report (RP506-3)

The use of laser excitation for enrichment of uranium isotopes, under intensive investigation at many laboratories, has received much publicity. Scale-up from present laboratory experiments to industrial practice requires extrapolation of laser and vacuum technology to reach reasonable efficiency, reliability, and producibility. For some cases of interest, it is evident that the requisite laser has not yet been obtained on even a laboratory scale.

The EPRI-sponsored effort described in this report does not judge laser isotopic separation or the most probable path of its development. Instead, a basic evaluation was undertaken of the prospects for reducing the demands on laser technology, which might be offered by atoms in highly excited states (high Rydberg number atoms). The purpose of this study was to demonstrate that such excitation could be achieved and is in principle applicable to isotopic separation. It also became apparent during this investigation that extension of available laser wavelengths might simplify scale-up problems related to throughput. This report provides a background study of laser isotopic separation methods together with a description of field ionization methodology and experiments. *Stanford Research Institute*

LWR Fuel Rod Modeling Code Evaluation

NP-369 Final Report (RP397-1)

This document presents the details and overall conclusions for Phase III of this LWR fuel rod modeling code evaluation.

Six fuel rod modeling codes were evaluated for potential use by the electric utility industry. The evaluation consists of a summary and qualitative comparison of relative code attributes and weaknesses, and a ranking of the codes according to objective and subjective criteria. The codes have been ordered as follows: COMETHE-IIIJ (1), BEHAVE-4 and LIFE-THERMAL-1 (2), GAPCON-Thermal-2 (4), and CYGRO-3 and FMODEL (5). COMETHE-IIIJ is generally the most versatile and accurate and is easy to use and relatively inexpensive to run. Belgonucleaire, developer of the COMETHE code, has thoroughly documented its foundations and improvements and has benchmarked it against a more extensive data base than was utilized in this project. The COMETHE code is available to U.S. utilities through EPRI and will be included as the deterministic code in Task 1E of the forthcoming modeling project (RP971). *Combustion Engineering, Inc.*

PLANNING

EPRI Economic Assessment Workshop

PS-310-SR Special Report

This report presents the proceedings of the Economic Assessment Workshop held in Chicago in September 1975. Participants from the electric utility industry and from EPRI staff discussed utility methods of economic assessment, system analysis, and application criteria as related to the selection of new technologies for use by the industry. Guidance was provided for establishing EPRI's methods and criteria for technology assessment, economic evaluation, and cost-benefit analysis.

Included is a detailed report of the discussions of three task groups: evaluation criteria for R&D alternatives, application of economic assessment to R&D planning, and application of system analysis techniques to R&D planning.

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