Modelers and Decision Makers

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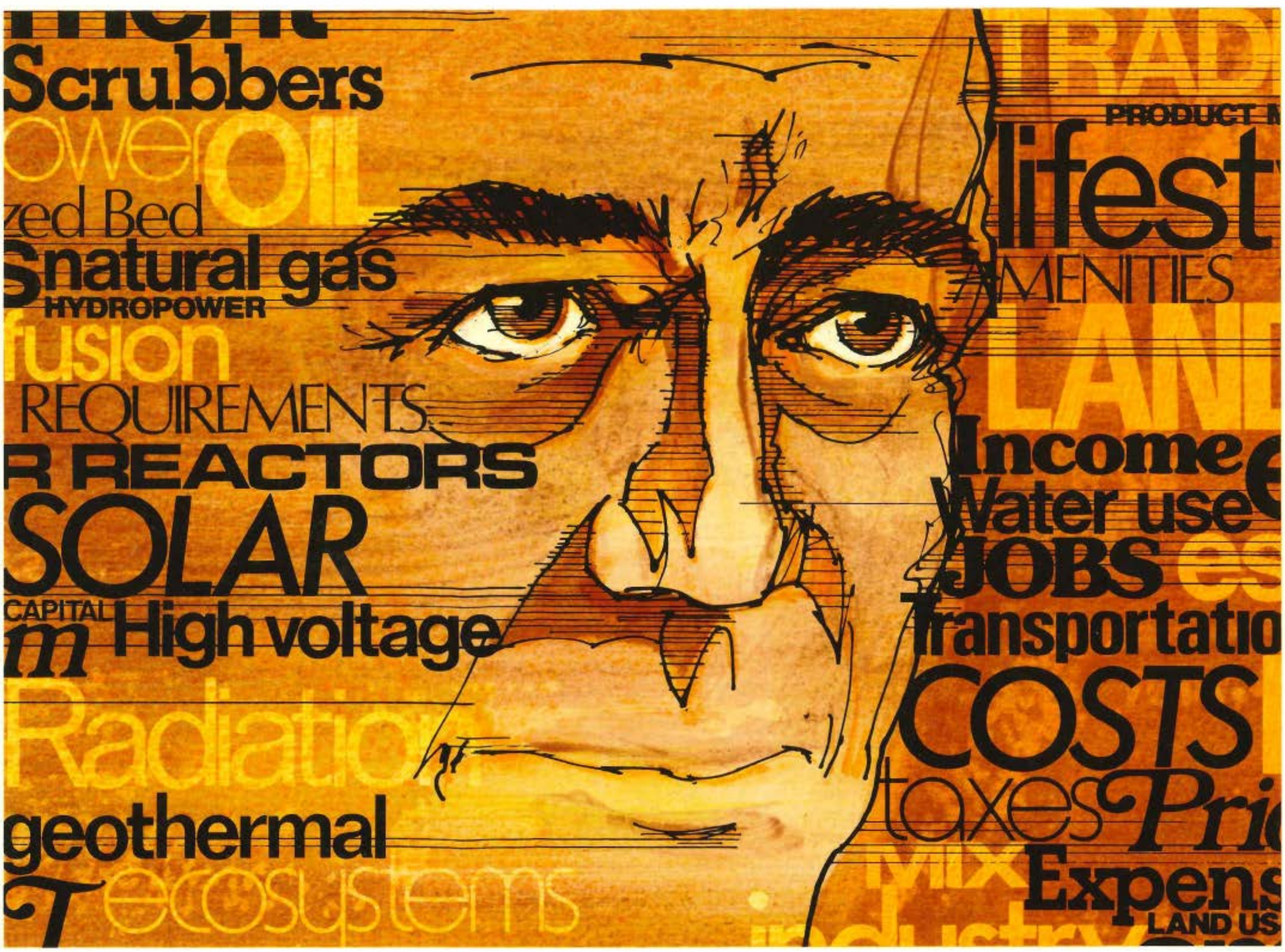

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Cover: Energy decision makers are beset with a numbing complex of information. More insightful energy decisions can be achieved by mutual understanding and closer partnership between modelers and decision makers.

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Prying Open Those Black Boxes

Martin Greenberger, the author of this month's cover article, has noted elsewhere that "model builders are creative carpenters, artful designers, and synthesizers who select their instruments of construction from any of several toolboxes." In his article, the manager of EPRI's Systems Program invites utility decision makers to play a more active and intimate role in this highly creative model-building process. He also describes EPRI's attempts to pry open and evaluate for decision makers the inner workings of several computer "black boxes"—models that can greatly influence the choice of solutions to energy problems. Both activities reflect Greenberger's long-standing efforts to build bridges of communication between the developers of models—in this instance, energy-economic models—and the users of the information that is assembled, organized, and analyzed by the models.

In his wide-ranging study, *Models in the Policy Process: Public Decision Making in the Computer Era* (New York: Russell Sage Foundation, 1976), Greenberger examined the difficulties in getting computer models that link many scientific disciplines to serve the user's immediate decision-making needs. More often than not, these hard-pressed users are only scantily informed about the murky innards of the black boxes. Greenberger cogently argues that understanding by active participation is a sounder basis for the use of models than faith alone.

Greenberger is realistic. He recognizes that "curves and numbers generated by a computer give the appearance of objectivity and authenticity, especially when presented by a soft-spoken young man who receives criticism graciously and quickly acknowledges the tentativeness and tenuousness of the results." He therefore argues for a third-party, objective appraisal of both the models and their smooth-talking builders.

The fact is that energy-economic models and their artful designers are clearly needed. When properly built and used, models are the "best technique yet devised for representing complex interactions and integrating disparate research." EPRI, for example, needs them in determining R&D priorities. Electric utility managers need them in carrying out a wide range of responsibilities: systems planning, dispatching, corporate finance, and so on.

Although economic modeling is not a panacea and can sometimes be (as Nobel Laureate Gunnar Myrdal described it) an "aberration into superficiality and irrelevance," it is also, like information generally, a source of power. Massive and almost instantaneous manipulation of data has become the touchstone of decision making in both the private and the public spheres.

One example, based on FEA's effort to assess the desirability of specific electricity rate design alternatives, will suffice. FEA is designing a model to analyze the response of electricity demand to changes in rates or other regulatory policies and to assess the desirability of an accelerated federal effort to encourage—or even require—the adoption of selected utility rate structures and regulatory reforms. This complex computer model of the utility industry is handicapped so far by a severe lack of data.

In an interim report to Congress, FEA therefore refrained from drawing conclusions about the desirability of rate reform on the grounds that the model was not yet developed. Then, a few months later—still without a model—FEA made its decision and recommended federal legislation.

Thus, we see, power is the province of the decision maker. The model alone is an elective instrument in exercising this power. As such, it needs to be better understood. Nevertheless, decisions can—and often must—be made without waiting for what a modeler's artful design might reveal.

Robert G. Uhler

Robert G. Uhler, Director
Energy Analysis Department
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Authors and Articles

■ Models that simulate energy-economic relationships are still new enough to be unfamiliar—and even downright mysterious—to many people they are intended to serve. Those who find these models unfamiliar may simply lack firsthand knowledge of particular mathematical techniques, although they are well equipped to remedy that deficiency. Persons who find models mysterious, however, may be unaware that communications lie at the heart of the modeling process. They need to learn how facts from disparate disciplines (often in different "languages") can be made compatible under a single linguistic umbrella and can be made to "talk" so that dynamic interactions can be explored.

Martin Greenberger speaks to the latter audience in this month's featured article, **"Closing the Circuit Between Modelers and Decision Makers"** (page 6), as well as in the ongoing research he guides as manager of the Systems Program in EPRI's Energy Analysis and Environment Division. Much of that program concerns effective communication between modelers and the people who rely on models to shape their own decision processes.

Greenberger is thus a facilitator and a teacher. Indeed, he began as a teaching fellow at Harvard, where he earned his BA, MA, and PhD in applied mathematics. He later taught for nine years at MIT's Alfred P. Sloan School of Management before joining the faculty of Johns Hopkins University in 1967. Greenberger is now completing a two-year term on loan to EPRI, and in January 1978 he will return to Johns Hopkins as a professor of mathematical sciences and senior staff associate of the university's Center for Metropolitan Planning and Research.

■ Coal is cheaper. No, nuclear is cheaper. The argument has flowed from coast to coast and from Canada to the Gulf in attempts (at best) to characterize a single preferred choice and (at worst) to disqualify one or the other fuel and power plant technology.

Charles Rudasill takes a rational course in **"Comparing Coal and Nuclear Generating Costs"** (page 14). Reviewing the results of several EPRI-sponsored studies, he presents a picture of six geographic regions, each of which is probably the largest area where generalizations are valid. Yet the data still appear as ranges and not as single-point values. The best that can be said, for EPRI's immediate purposes, is that a deeper understanding is being gained of the parameters influencing coal and nuclear power generation costs and that consistent bases of appraisal are becoming available.

A member of EPRI's Planning Staff since 1975, Rudasill has brought with him 28 years of experience at Virginia Electric and Power Co. in its engineering, operations, and planning functions. Most recently he was responsible for coordinating Vepco system planning with that of neighboring utilities—work that involved him with the Southeastern Electric Reliability Council, the National Electric Reliability Council, and various interregional coordinating groups. At EPRI he is responsible for the methods used to determine the potential value to utilities of EPRI research results.

■ Technology transfer is another area in which effective communication is essential to success. The process and its prerequisites are traced **"From Bench to Busbar"** (page 18) by JOURNAL staff writer Stan Terra, with help from Richard Schulte, EPRI's manager of Program Plans.

In our preoccupation with dollar budgets, it's easy to forget that the key concept of good communication is involvement. And when it comes to moving research results into the working world, involvement is more than a single link between researcher and end user. For the electric power industry, it's an entire chain connecting planners, manufacturers, marketers, regulators, end users, even the public, and—of course—budget directors.

■ As inspection requirements are tightened for nuclear power plants, inspection methods begin to fall short, if only in their ability to get at concealed surfaces and welds, for example. EPRI is doing something about it by sponsoring the development of an X-ray apparatus that is light enough for two persons to carry. The unit can even look at welds from inside a pressure vessel nozzle. Eugene Reinhart, project manager for nondestructive testing, is in charge. **"Portable Radiography for Power Plants"** (page 20) was written by John Kenton of the JOURNAL staff.

■ What can higher education do? Sometimes people think it can do the impossible. Commentary on the education controversy has been distilled from observations by Purdue University's president in **"Arthur Hansen: Engineering Education to Fit the Times"** (page 23). Hansen is a member of EPRI's Advisory Council and was interviewed by Barry Sulpor, manager of the EPRI news bureau.

A mathematician by training, and one of the country's foremost engineering educators, Hansen discusses the role of the engineering student in a world growing more technologically complex each day. Intrigued by both the potential and the limitations of higher education, he suggests that "instead of wondering how the engineering student can become a 'whole person' without taking courses in nonengineering fields, it might be better to ask how the nonengineering student can become a whole person without taking courses in technology."

■ It's tempting to think of energy conservation in terms of direct fuel savings alone. It's tempting, but it's simplistic. Even fractional improvements have become costly, so the R&D goal must include something besides fuel. In that way, the overall economics are maintained, perhaps even improved.

"Superconductivity in Power Generation" (page 54) provides a good example of saving fuel through greater efficiency and, in addition, saving something else to make it cost-effective. EPRI's **Mario Rabinowitz** explains how the phenomenon of superconductivity remarkably alters ac generator properties by cutting electric losses by half. At the same time, it offers to pay for its own development and adoption by requiring as little as half the generator size and weight for a given output at the improved efficiency.

Rabinowitz earned his BS and MS degrees at the University of Washington and then added a PhD at Washington State University. He was a George F. Baker Scholar. His research assignments have included The Boeing Company, the Westinghouse Research Center, Varian Associates, and the Stanford Linear Accelerator Center. After seven years at SLAC, he joined EPRI in 1974, specializing in cryogenics for power generation and transmission applications. He is now the senior scientist for EPRI's Electrical Systems Division.

Greenberger

Rudasill

Rabinowitz

crubbers
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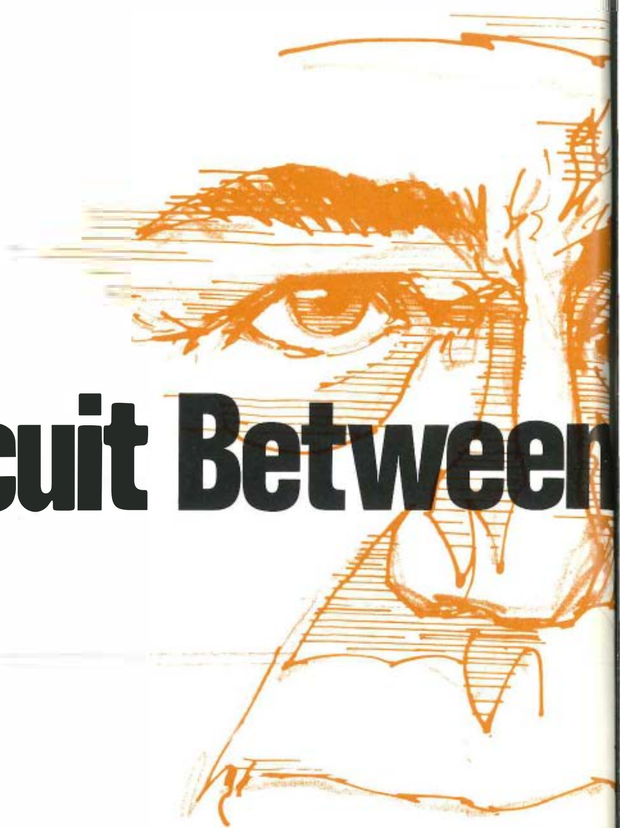
High voltage



Closing the Circuit Between

Discussion these days about the energy problem is so common that some people may get the idea that energy *is* a problem. Food is also often thought to be a problem. Energy and food are not problems. Energy is the capacity to do work and food is the earliest and most immediate provider of this capacity.

In the body, food undergoes chemical change and produces energy through oxidation. A normal body uses the energy from food at the rate of between 1000 and 4000 kilocalories a day, on the order of about one-tenth of a kilowatt (kilowatthours per hour).

Before the taming of fire, food was the only source of energy for doing work. Today, modern technology provides usable energy in several other forms, such as heat and electricity. These additional energy forms can multiply the use of energy over that obtained from food as much as a hundredfold. The United States, for example, consumes energy at a rate of about 10 kilowatts per person, approximately four times the world average, and a hundred times the per capita rate of energy Americans obtain from food.

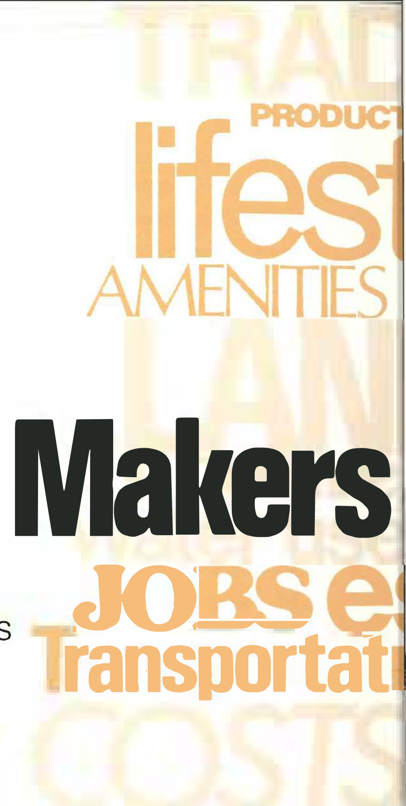
Martin Greenberger is manager of the Systems Program in EPRI's Energy Analysis and Environment Division.

The energy problem

The point suggested by these statistics is that although food and energy are not in themselves problems, their lack or scarcity relative to a country's appetite and state of development can indeed create problems. Food becomes a problem when people go hungry and children are undernourished. Energy becomes a problem when lights go out and gas tanks run dry. These are the extreme conditions that an economy works to avoid by giving out various cautionary signals: a fast rise in oil prices, brownouts, long lines at the gas station, the unavailability of new contracts for natural gas.

The alarm has been sounding loudly and often in the past few years, making the slogans "energy problem" and "energy crisis" favorites among the ready clichés of journalists and politicians. Slogans are the means by which newspapers are sold, people aroused, and votes won. Although arousing people cannot, by itself, alleviate energy shortages or prevent interruptions in service, it can encourage the study and solution of underlying problems, as evidenced by the establishment in 1973 of the Electric Power Research Institute.

The first step in studying a problem is to delineate and phrase it. Ask five people what the energy problem means to them and you will probably get five different answers. There is good reason. The cost and availability of energy can directly affect your budget, taxes, and comfort. Indirectly, energy can influence your lifestyle and job: the car and house you buy, where you live and work, whether you work, how much you earn,



Modelers and Decision Makers

Energy decision makers facing hard choices are helped more by a simple understanding of system interactions than by copious computer printouts or dreary displays of numbers. by Martin Greenberger

An EPRI state-of-the-art feature

the quality of the air you breathe, the views you see. Energy impinges on the functioning of industry, the use of land, transportation patterns, international trade balances, and the overall price level. The production, distribution, and consumption of energy can cause reverberations throughout the immediate environment, the economy, and the entire ecosphere.

With such broad ramifications, energy issues take on a chameleonlike character that presents difficult choices for decision makers. The energy industry focuses on the issue of finding the means for providing energy efficiently, cleanly, safely, and in amounts adequate for a sound economy. But how much is adequate? Some environmentalists turn the question around and urge a reduction in the nation's appetite for energy. They challenge the proposition that the more energy, the better the life. They point out that for some individuals less food is healthier than more, and they argue that the same applies to energy and the health of the ecosystem.

Energy decision making

The subject of energy has two sides as shown above. To the right are the varied effects emanating from the use of energy. To the left is the equally broad and diverse span of technologies, fuels, and other resources entering into the supply, conversion, distribution, and consumption of energy.

Energy decision makers sit between these two sides of energy. To the right, they must be sensitive to the many direct and indirect effects of their actions. To the left, they must draw on information and expertise from a staggering assortment of fields, such as economics, finance, environmental science, nuclear physics, geology, and almost every branch of engineering. Understanding the significance of research in these fields is a formidable task, and not only for the decision maker. It is sad but true that an economist and an engineer in the same country often have more difficulty understanding one another than either has understanding a member of his own discipline in a foreign country. It can be harder to cross the barriers between disciplines than between nations.

Intelligent energy decisions call for good research. But energy decision makers require more than that. Because research results flow from many different fields, decision makers need a means for integrating the dissimilar and often incongruous results of this research. They need a way of resolving inconsistencies and conflicts and of weighing the spectrum of interests and objectives they seek to serve. There is a need for structure in considering these issues to enable the information and findings of the various studies on the left to be applied to the problems on the right. There is a need for interpreting the many technical languages used in these research studies and for providing decision makers with a clear appreciation of the lessons learned.

What all this translates into is a general requirement for more effective communication and improved understanding between energy researchers and energy decision makers and among energy researchers in different fields.

EPRI has been working to promote better communication through a coordinated set of research projects launched within the past 15 months. To describe these projects requires some technical terms that may be mysterious to the nonspecialist. These terms are associated with the increasingly important (but still esoteric) practice of computer modeling.

Energy-economic models

The best technique yet devised for representing complex interactions and integrating disparate research in the energy field is the energy-economic model. An energy-economic model is a set of quantitative relationships and logical interconnections expressed in a symbolic way that can be explored, or run, on an automatic digital computer. These models, despite their limitations, are becoming commonplace in energy analysis these days because of their ability to deal with the highly complex and convoluted nature of energy problems.

Modeling is not the tool or private preserve of a single discipline. Engineers, economists, and operations researchers have different types of models. In fact, there are a growing number of models that combine the best features of the modeling methodologies of many disciplines. An energy-economic model provides a basic framework for integrating research from different fields. It is a mechanism by which workers in these fields can join together, work cooperatively, and begin to appreciate the significance of one another's efforts.

The variety of modeling methodologies applied to energy research reflects the diversity and richness of the subject matter. The methodologies include sets of econometric equations; input-output tables; optimization procedures, such as linear programs; engineering process descriptions; net balancing and general equilibrium techniques; institutional and financial relationships; system dynamics; and judgment exercised within accounting frameworks.

The last category is the simplest to explain. It is the application of judgment systematically within a comprehensive structure that accounts for important effects and provides consistency in checks and balances—the epitome of what the energy decision maker desires. The other modeling methodologies are formal approaches. They draw on the modeler's understanding more in the creation of the model than in its operation. With all these modeling approaches, judgment is of paramount importance in interpreting the model's results.

Energy-economic models are often divided between those that are primarily econometric in formulation, stressing economic considerations and employing historical time series data, and those that are mainly engineering in orientation, using optimization procedures and technological process descriptions. The econometric approach uses statistical methods to anticipate what will happen tomorrow based on what occurred yesterday; that is, based on past patterns, relationships, and trends. The optimization approach, instead, looks ahead by algebraically determining the best (e.g., most cost-effective) set of alternatives, based on what is known or assumed about future resources and technologies. Both approaches have their strengths and weaknesses. Traditionally, energy modelers have tended to use the optimization approach to represent the supply side and the econometric approach to represent the demand side. But these distinctions are tending to become blurred as models are expanded and merged and as modelers from different disciplines learn and borrow from one another.

Table 1 is a sampling of the better-known energy models. Shown next to each model is the primary but not necessarily only methodology used on both the supply and the demand sides. Also indicated are the model developers and some of the uses of the models in energy decision making. The table illustrates the increasing array of energy modeling activities and applications that has been developing in recent years. It suggests the difficulties confronting decision makers trying to comprehend and assimilate the significance of this expanding research.

Communication gap

From the frequency of model use in the energy field, one may get the impression that energy decision makers are sophisticated about the workings of models. This is not so. Decision makers are not direct users of models. They do not plug their questions directly into models any more than housewives plug their toasters directly into power generators or music lovers connect their stereos directly to the microphones at Carnegie Hall.

Transmission of electricity to the consumer requires a distribution network. Propagation of radio signals to the listener requires a broadcasting system. What does communication of research to the decision maker require?

It requires more than communication cables carrying computer-generated tables. Effective communication between the energy research and decision-making communities requires a level of understanding between the two groups that for the most part is still lacking.

Yet, energy models do influence decision making—more than many decision makers realize or acknowledge. The influence of models on decision makers tends to be indirect and often roundabout—a chance remark by a respected associate at a meeting, a story told over coffee, a reference in a newspaper editorial, a comment made by a television reporter. Many decision makers try to set up systematic communication channels through

Table 1
MODELS, METHODOLOGIES, AND USES

Model	*Supply Side*	*Demand Side*	*Uses*
Adams-Griffin	Optimization	Econometric	Strategies for oil refinery pricing.
Baughman-Joskow	Optimization	Econometric	Energy-economic effects of nuclear moratorium in California.
Bechtel Supply	Accounting	Exogenous	FEA studies of industry requirements for energy expansion.
Brookhaven (Hoffman)	Optimization	Exogenous	ERDA evaluation of alternative energy technologies.
Coal 1 (Naill)	System dynamics	System dynamics	Congressional hearings on energy forecasts.
DRI-Brookhaven*	Optimization	Econometric	ERDA studies of economic impact of alternative energy futures.
Dupree-West	Exogenous	Exogenous	Department of Interior long-term energy forecasts.
Emergency Energy Capacity	Optimization	Exogenous	Office of Energy Preparedness and Treasury Department storage option studies.
ETA and ETA-Macro (Manne)	Optimization	Informal econometric	Studies of nuclear alternatives (Ford-Mitre, Committee on Nuclear and Alternative Energy Systems).
FEA Short-Term Petroleum	Optimization	Econometric	FEA studies of oil embargo.
Hudson-Jorgenson*	Econometric	Econometric	Impact of reduced energy consumption on the economy (Ford, EEI).
Hynilicza*	Econometric	Econometric	Alternative strategies for optimal economic growth.
Illinois Input-Output (Hannon and Bullard)	Econometric	Exogenous	ERDA studies of energy conservation.
Kennedy-Niemeyer*	Econometric	Econometric	Macroeconomic effects of a nuclear moratorium in California.
Lawrence-Berkeley (Glassey)	Optimization	Partial optimization	EPRI industry studies.
MacAvoy-Pindyck	Econometric	Econometric	White House analysis of gas deregulation.
Nordhaus Bulldog	Optimization	Econometric	Energy economic impact of alternative nuclear and fossil fuel strategies (Committee on Nuclear and Alternative Energy Systems).
PACE	Optimization	Exogenous	Energy sector studies with emphasis on petro-chemical industry.
PIES	Optimization	Econometric	National energy plan and FEA studies of oil and natural gas price decontrol.
PILOT (Dantzig)*	Optimization	Partial optimization	Exploration of potential energy-economic growth.
SEAS (House)	Exogenous	Exogenous	Economic and environmental impacts of alternative energy futures.
SRI-Gulf (Cazalet)	Process representation	Informal econometric	Gulf Oil Co. and White House decisions on synthetic fuels.
TERA (Limay)	Optimization	Econometric	American Gas Association natural gas studies.
Wharton (Klein)*	Econometric	Econometric	Congressional hearings on Carter energy plan.

*Models used in the first study of EPRI's Energy Modeling Forum project.

Glossary

Accounting: Charts of requirements and characteristics displaying numerical relationships.

Econometric: Mathematical (difference) equations solved simultaneously, with coefficients estimated statistically from historical data.

Exogenous: Given or assumed, rather than calculated (endogenously) within the model.

Optimization: Determination of "best" solutions by means of algebraic procedures.

Process representation: Description of energy processes and markets in the form of a hierarchical network.

System dynamics: Mathematical (integral) equations solved recursively with coefficients estimated judgmentally from the modeler's experience and intuition.

trusted staff aides and others they know well and in whom they have confidence. The staff aide, for example, may be charged with staying abreast of relevant research in the field.

Ideally, this assistant would be all-wise and all-knowing. When the decision maker is confronted with a question that requires immediate scrutiny, as is typically the case, he would turn to this oracle on his staff for the latest information and a comprehensive analysis. But the truth is that even the most intelligent staff member is hard pressed to find the time to perform this kind of service. Instead, he becomes a minuteman, scurrying for facts and figures when the bell sounds.

The Washington office of one congressman prominent in energy affairs has been described as a cross between the city room of a metropolitan newspaper and the floor of the New York Stock Exchange. Regrettably, this pressurized atmosphere is more characteristic than caricature, and it is not likely to change appreciably in the foreseeable future.

The combination of too much pressure and too little time causes the decision maker, through his staff, to attach excessive importance to information and analyses that are readily available or just released. Without sufficient time to personally study the issue carefully and to weigh fully the arguments of all points of view, decision makers tend to look for and favor arguments supporting their own positions. They forsake the most cogent for the most congenial analyses.

Busy decision makers and their harried staffs are not able to enter meaningfully into the world of the modeler. Even if they had more time, most decision makers would choose to spend it in ways more in tune with their own interests and priorities. Conversely, the world of the decision maker appears frenetic and disorganized to the methodical, reflective modeler who is glad to remain within the boundaries of his own domain.

Need for bridges

Energy research currently is a marketplace of ideas, data, studies, and pronouncements. This is healthy and desirable. But the producer (the modeler) is often out of touch with his ultimate and most important consumer (the decision maker), while this consumer does not understand the wares of the producer. The producer does little market research, and the consumer has no reliable shopping service. Under these circumstances, a marketplace will not operate efficiently or to best advantage.

The need for sound energy decisions has never been more pressing than now. Energy modelers have a great deal to offer, but they need better signals from decision makers on the nature of the problems, on the constraints, and on what is and is not critical. Decision makers need a better understanding of the models, their assumptions, strengths, and limitations, and on why they produce the results they do. The need for bridges is great on both sides of the gulf, and the responsibility for creating these bridges is a shared responsibility. Recognizing this fact is a first and crucial step. Both sides can contribute, whereas either side working alone is limited in what it can accomplish.

Transfer project

To facilitate better communication, the Systems Program at EPRI is experimenting with a number of ways to bring the information obtained from modeling to decision makers. One such activity, the transfer project, is designed to transfer the methods, results, and expertise from certain EPRI research projects to EPRI's member companies. The project selects research of particular interest to the utilities and directly involves analytic staff and decision makers at the companies in applications of this research. Active participation makes the research results far more meaningful to the companies than would the reading of a final project report by itself.

An example of a transfer project is a current effort to quantify the costs and benefits of providing more rather than less generating capacity. Participating utilities are Pacific Gas and Electric Co., the Tennessee Valley Authority, Wisconsin Electric Power Co., and Long Island Lighting Co.

Communication is a two-way street. Utility companies can provide important input to the transfer project by drawing on their supply of people, information, experience, and know-how. A senior official of each utility serves as liaison for the project and oversees the members of the company involved in the research.

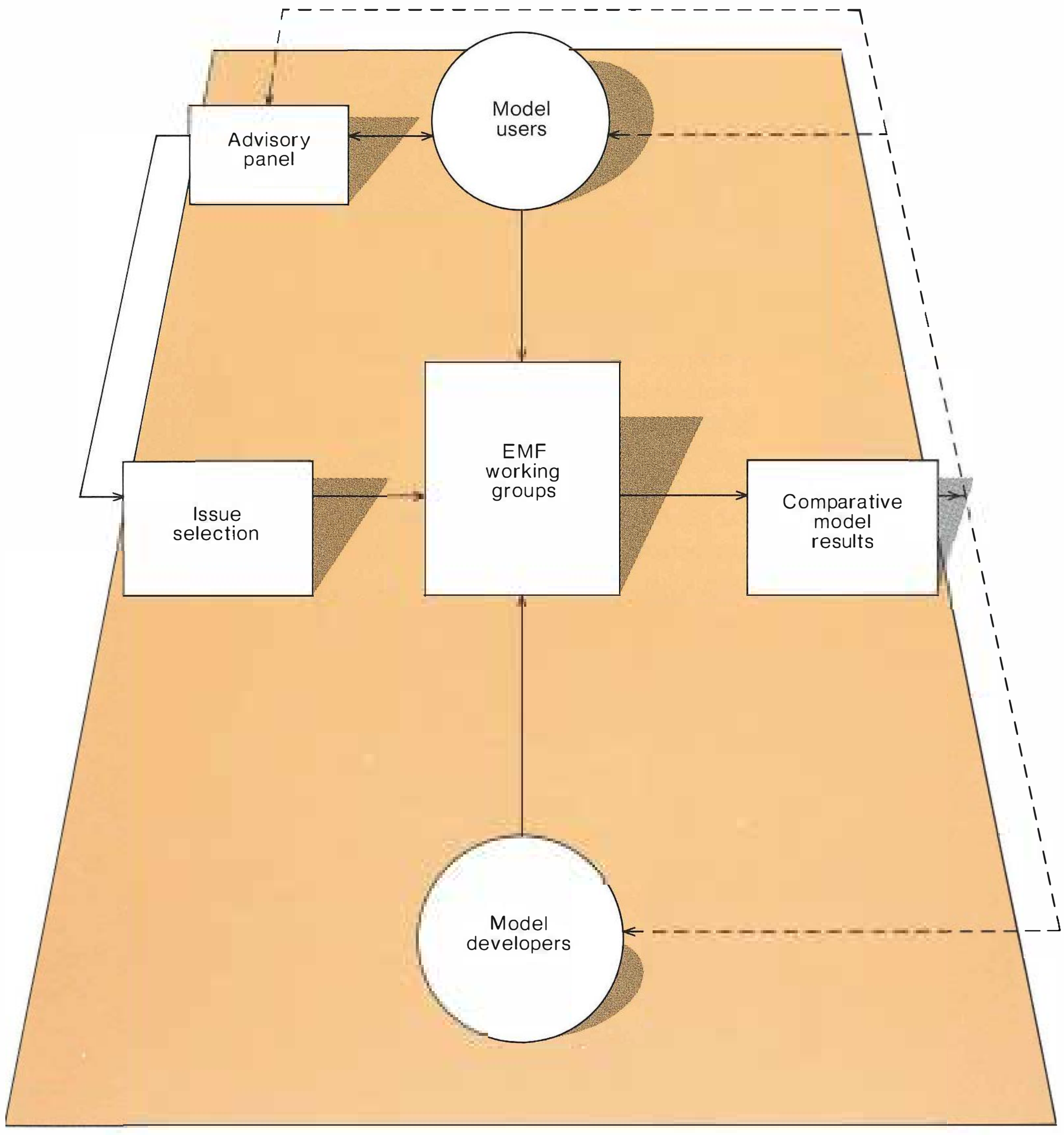
Energy Modeling Forum

Another communication bridge well along in its development is an ongoing process of energy-economic model analysis called the Energy Modeling Forum (EMF). The project, set up at Stanford University in mid-1976, is led by William Hogan, formerly of the Federal Energy Administration (FEA) and now a faculty member at Stanford. It is a bridge that is working.

Subjects for investigation are selected in consultation with a senior advisory panel of top energy decision makers and analysts chaired by Charles Hitch, president of Resources for the Future, Inc. Selection criteria include the timeliness and importance of the subject; its susceptibility to different conclusions and points of view; the models that can be used in its analysis; and the model developers and users that the analysis can involve.

The first issue examined was the relationship between energy and the economy. The study investigated the role of energy in economic growth. Many think energy and the economy are closely linked, based on the apparent lockstep between historical series of energy use and national income. Currently rising energy prices and curtailed energy supplies represent a departure from past patterns.

Energy Modeling Forum process involves model developers and users working together to study a topic chosen in consultation with the advisory panel, a group of senior energy policymakers and analysts. The working group agrees on a set of computer runs to be made under standard assumptions by using a number of models appropriate to the subject under study. Preliminary results of the runs are compared and used to identify model deficiencies, inconsistencies, and misunderstanding. Final results are discussed with the advisory panel and published for wide distribution to the energy decision-making and research communities.



This raises the question of whether there are enough substitution possibilities among energy and other production factors in the economy to enable energy use to be reduced without slowing the economy's advance.

The six models chosen for the first study are asterisked in Table 1. Developers of these models joined in a working group with a larger number of model users and decision makers from electric utilities, other energy industries, and government agencies. The group agreed on a number of energy scenarios structured to highlight the questions being examined. They initiated a series of computer runs, compared the results, made corrections, ran refined analyses, discussed the findings with the advisory panel, and then prepared an EPRI report for distribution to the energy-modeling and decision-making communities at large. Here are some of the conclusions from this report:

- In the presence of constant energy prices, increases in economic activity produce similar increases in energy demand, although these may be moderated by trends toward less energy-intensive products and services.

- Higher energy prices or reduced energy use need not produce proportional reductions in aggregate economic output. There is a potential for substituting capital and labor for energy, and the contribution of energy to the economy relative to these other factors of production is small.

- The models nevertheless do show some significant reductions in economic output resulting from higher energy prices. The magnitudes of these reductions are very sensitive to the substitution assumptions implicit in the models. Further, the impacts may be large for individual sectors of the economy.

- The benefits of energy substitution may be lost in part if energy scarcity impedes capital formation. Reduced energy inputs cause lower levels of investment and, consequently, reduced potential GNP. This indirect impact may be the most important effect of energy scarcity.

As its second topic, EMF is examining the problems and constraints associated with a U.S. return to major reliance on coal. Choice of this subject permitted the selection of an entirely new slate of models, and there has been a corresponding revision in the composition of the working group. The second working group is chaired by David Sternlight, chief economist of Atlantic Richfield Co.

Model assessment

Complementing the EMF project is a model verification and assessment facility established at MIT. This facility performs overview and in-depth assessments of selected models of special interest. Like the EMF, the MIT project provides focused insights and evaluations, rather than voluminous numerical output of uncertain relevance or cumbersome technical detail for its own sake.

The next order of business is to distribute the results of these projects widely and make the findings clear and understandable. The modelers, model users, and decision makers personally participating and actively contributing to the projects are clearly benefiting. While many people other than those within the immediate orbit of the activities are kept informed and are profiting from what is being learned, much more needs to be done. It will take the efforts of many people and organizations to achieve the ultimate goal of generally improved communications between researchers and decision makers in the energy field.

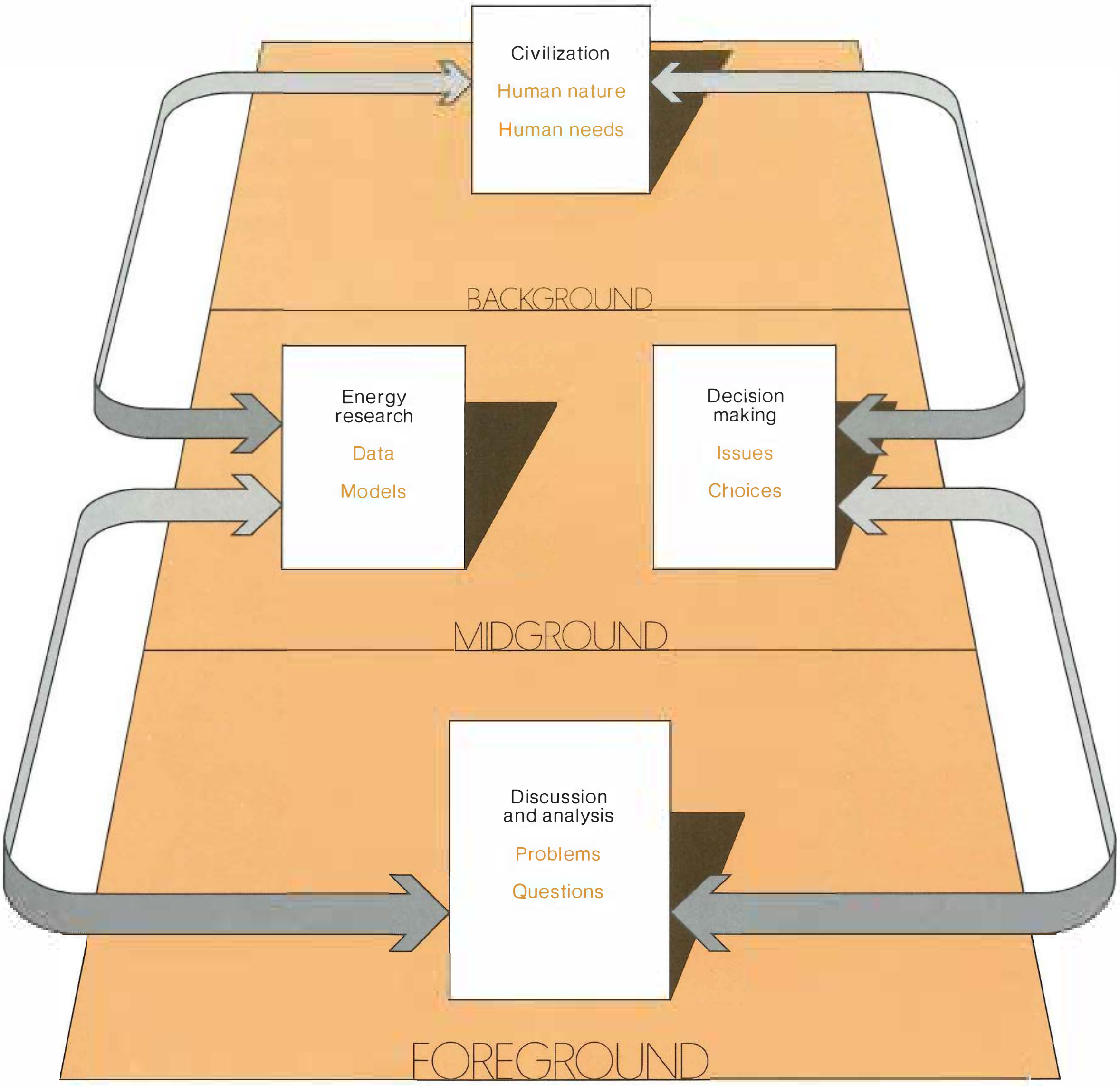
Problem focus

Modeling research presents energy decision makers with a promising means to achieve a better understanding of the problems and choices before them. To develop the potential of this research and take advantage of it, decision makers must involve themselves in the kind of give-and-take with model developers that will bring them closer, not to the technical workings of the models, but to the questioning and deepened comprehension that modeling exercises can provide.

There is one thing that most creative modelers and decision makers definitely share. They love problems, especially problems they can solve or handle, each in his own way. Discussion and analysis of energy problems provides a common ground on which energy model developers and decision makers can meet. That is why EPRI's transfer project, its Energy Modeling Forum, and even to some extent, its Model Verification and Assessment Facility insist on centering their analyses on concrete energy problems. The problem orientation helps focus the research on the interests and priorities of energy decision makers and makes it easier for these decision makers to compare and appreciate what the models are saying and why.

Energy decision making and energy research can be thought of as taking place in a midground. Little direct communication occurs between decision making and research, although both derive from and refer back to the fundamental needs and values of human life. What is being experimented with in the EPRI projects described earlier is the development of a communication process wherein decision makers and researchers learn from one another in the course of jointly analyzing and discussing energy problems of common concern. This communication process is a bridge that can aid in producing sounder, better-reasoned energy decisions. What is required to erect this bridge is for parties on both sides to show a sustained tolerance for one another, mutual respect, open-mindedness, and a willingness to become actively involved. It may be a great deal to ask but the cause is a good one. The need is great and the time is right.

Energy research and decision making can be portrayed as taking place in a *midground,* where direct communication between the two is minimal, although both derive from and refer back to basic needs and values of human life, shown in the *background.* Efforts such as EPRI's forum project are aimed at developing a communication process wherein decision makers and researchers emerge in a *foreground* and learn from each other while jointly analyzing and discussing energy problems of common concern.



Comparing Coal and Nuclear Generating Costs

by Charles L. Rudasill

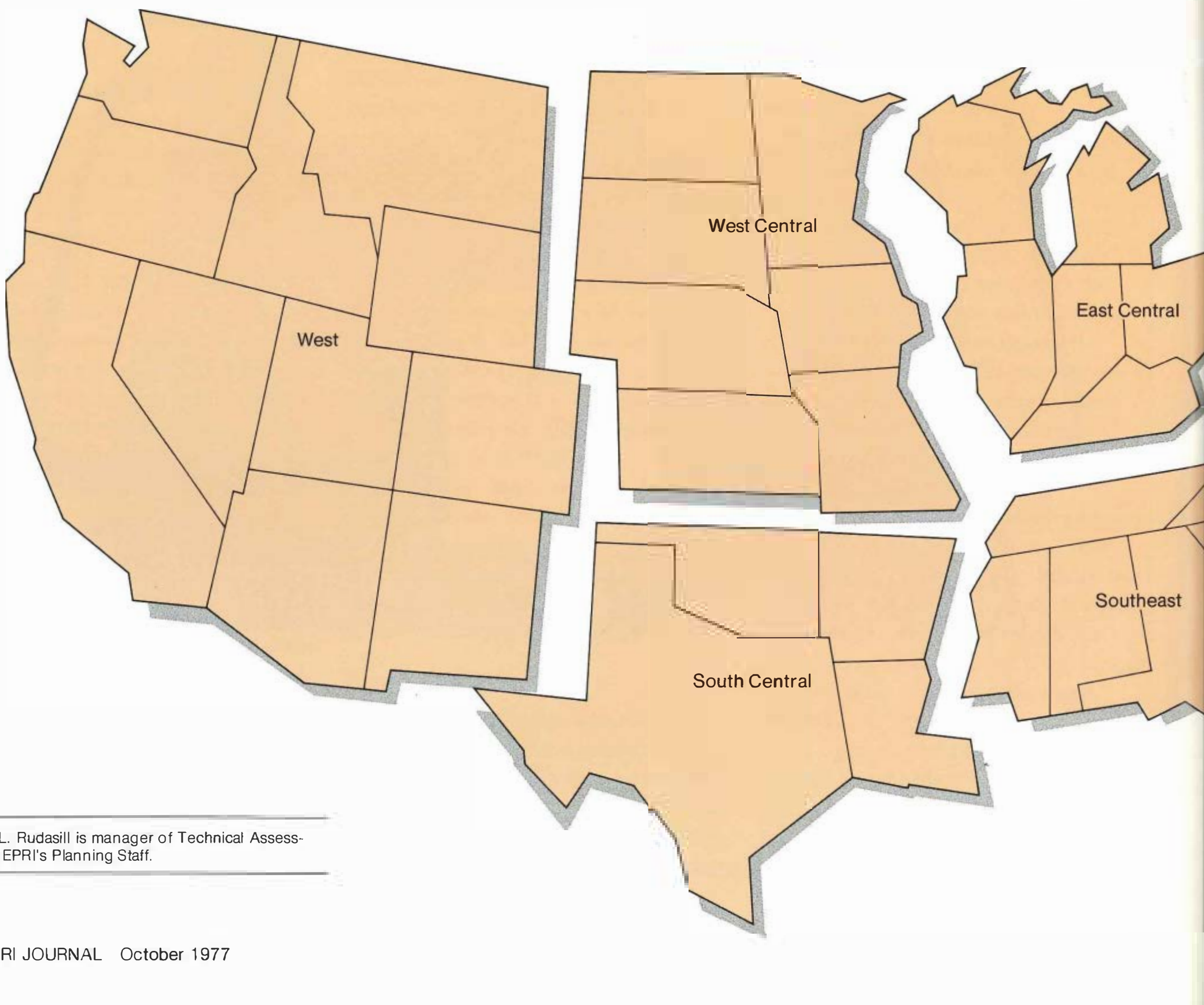
A new study by EPRI, based on differences in six regions of the United States, shows that both coal and nuclear generation can be economically attractive in all regions but nuclear has an average cost advantage.

There have been many estimates published on the costs of generating electric power with coal and with nuclear fuel. These range from detailed estimates related to specific sites to very broad estimates of "typical" costs for the nation.

It is not surprising that the estimates vary widely. It is important, however, for EPRI to have reasonable and consistent estimates of the cost of generating electricity by conventional means to provide a base for determining the potential value of new generating technologies. EPRI, therefore, has reviewed and analyzed the costs of producing electricity from coal and from nuclear power stations, using available technology with current safety and environmental regulations. (*Coal and Nuclear Generating Costs.* EPRI PS-455-SR.)

While it is clearly impractical for EPRI to consider all the site-related factors that can affect generating costs, it is unrealistic to consider any single set of geographic factors to be representative of an area as large as the United States. A regional approach has been taken by EPRI, with the country divided into six regions selected on the basis of general applicability of a specific power plant design and of region-specific cost parameters (Figure 1). Each of the six regions represents a different set of circumstances that affect generating costs, and these are consid-

Figure 1 The six regions of the United States analyzed in comparing power generating cost variations.



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ered sufficient for a general overview on a regional basis.

The analysis is thus more specific than studies using national averages, but much less detailed than those made by utilities' analyzing specific projects, in which local circumstances and requirements can significantly affect generation costs.

The specific objectives of the study were to:

- Understand the principal parameters that affect the cost of coal and of nuclear generation
- Identify uncertainty ranges in estimates of coal and nuclear generation costs
- Provide a consistent set of cost estimates for coal and nuclear generation that (although lacking the detail needed for specific project studies) can be useful in making general appraisals
- Establish base cost estimates that can be periodically updated as improved data become available

For an overview of coal and nuclear generating costs, levelized busbar costs were calculated on a regional basis. Because of the many uncertainties in forecasting future conditions, the cost estimates are presented in ranges. The ranges do not have any formal statistical significance, nor do they indicate extremes of what is possible; rather, they are ranges of what is considered to represent reasonably likely circumstances in an uncertain future environment. The overall results are shown in a bar chart (Figure 2), with the top portion of the bars representing the range of the estimates. These values are specifically based on generating units going into service in 1986. An assumed annual inflation rate of 6% has been included in all cost calculations, and total revenue requirements (with inflation effects included) have been levelized over a 30-year assumed unit lifetime. For ease of interpretation, the results have been expressed in 1976 dollars (1986 values $\div$ 1.06^{10}).

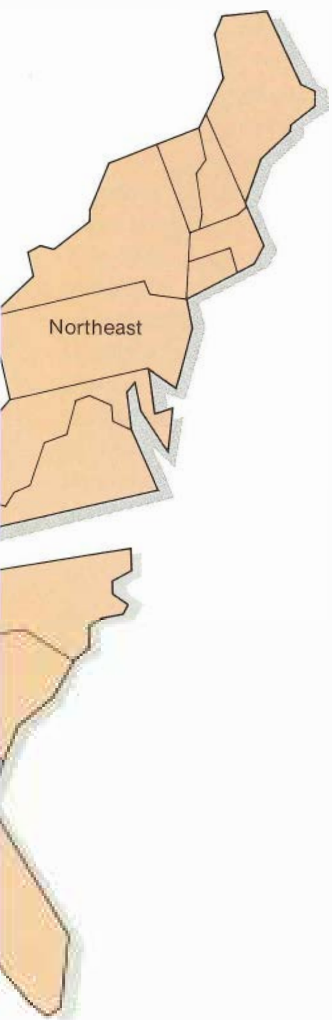


Figure 2 The top section of each bar represents the estimated range of levelized busbar costs for units entering service in 1986 (1976 $). The ranges indicate reasonable projected costs, not possible extremes.

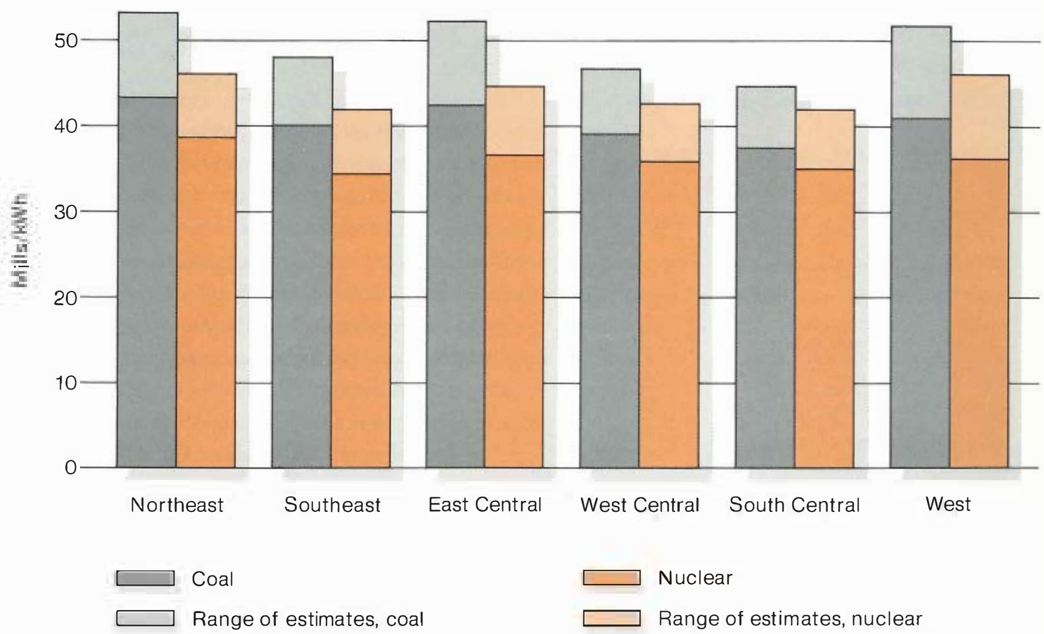
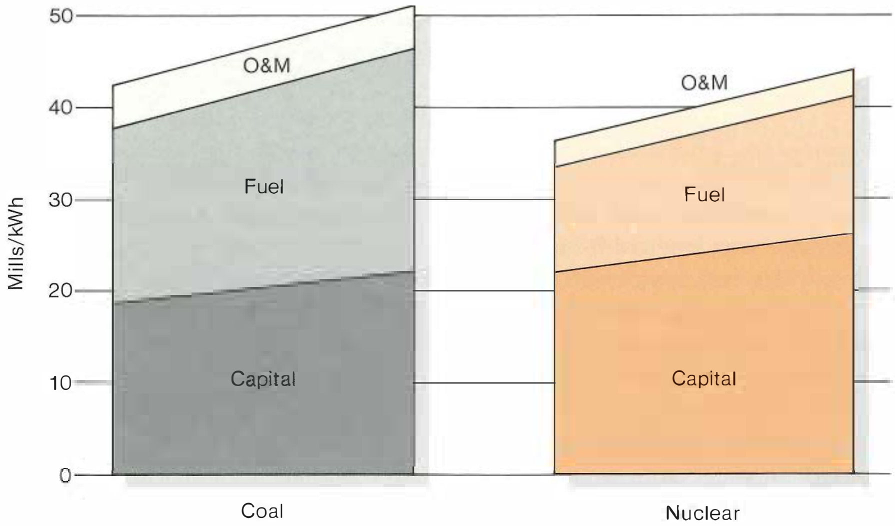


Figure 3 Breakdown of levelized busbar costs for a typical region shows capital costs, fuel costs, and operation and maintenance costs (1976 $). The sloping tops show ranges of the estimates.



A breakdown of the levelized busbar costs for a representative region separates levelized capital costs, fuel costs, and operation and maintenance costs (Figure 3). The sloping tops of the bars indicate the ranges of the estimates.

The overall results indicate that:

□ Both coal and nuclear generation can be economically attractive in all regions, depending strongly on local conditions.

□ Nuclear generation shows an *average* cost advantage over coal in all regions.

□ Average cost positions of coal and nuclear are closer together in the western part of the country, reflecting the generally lower cost of coal.

□ A new baseload generating technology must achieve 30-year-levelized total busbar costs of 35–45 mills/kWh in 1976 dollars to compete with existing technology on an economic basis.

Capital cost studies

Capital cost estimates were developed for EPRI by Bechtel Corp. for coal-fired generating plants and by United Engineers & Constructors, Inc., for nuclear generating plants. These estimates have been adjusted for consistency by the EPRI staff and adapted to the regional situations that have been established. The estimates include interest during construction, startup costs, contingencies, and so on. Land costs were not included because of the wide variation in land values. The capital cost estimates are summarized in Table 1.

The cost estimates developed for coal-fired generating plants were based on assumed locations selected to show the effects of regional differences in coal characteristics, labor rates, and site material costs. A common plant arrangement for a two-unit plant was used for each of the estimates; only minor variations were applied to adapt the basic arrangement to the sites and the coal types considered. All the estimates included flue gas desulfurization equipment appropriate for the coal assumed for each particular unit, and all units included high-efficiency (99.5%) electrostatic precipitators and mechanical draft cooling towers. All units were designed to meet the current (1976) requirements of the Environmental Protection Agency for new-source performance standards.

The flue gas desulfurization equipment significantly affects capital costs, representing nearly 20% of the cost of a generating unit (Table 2). Unit net heat rate is increased by additional auxiliary power requirements and by the need for reheating flue gas after desulfurization.

Table 1
CAPITAL COSTS—GENERATING PLANTS
($/kW in 1976 dollars)

Region	*Coal*	*Nuclear*
Northeast	638–759	757–901
Southeast	519–619	649–774
East Central	605–721	719–856
West Central	597–711	689–820
South Central	593–706	670–798
West*	618–810	713–934

*Higher costs include allowance for increased environmental and seismic sensitivities.

Table 2
CAPITAL COSTS—
FLUE GAS DESULFURIZATION
(in 1976 dollars)

Region	*$/kW**
Northeast	122–145
Southeast	99–118
East Central	117–140
West Central	82–98
South Central	116–138
West	85–111

*Included in the total capital cost values given for coal in Table 1.

Table 3
FUEL COSTS
($/$10^6$ Btu in 1976 dollars)

	Delivered Coal Costs	
Region	*1976*	*2000*
Northeast	0.88–1.14	1.04–1.35
Southeast	0.88–1.13	1.07–1.37
East Central	0.83–1.07	1.00–1.30
West Central	0.68–0.88	0.86–1.12
South Central	0.46–0.59	0.64–0.82
West	0.74–0.96	0.94–1.22

	Nuclear Fuel Cycle Costs	
	1976	*2000*
National	0.49–0.63	0.61–0.78

The capital cost for the coal plant located in the South Central region is based on burning lignite. Because of the high cost of transporting this low-Btu fuel, the capital cost of the coal plant in this region was increased to provide for additional electrical transmission distances (assumed as 100 miles) resulting from the economic incentive to locate lignite-burning plants close to the mines.

The cost estimates developed for nuclear generating plants were based on a reference design common to all regions. The nuclear steam supply system assumed was the pressurized water reactor type. All regulatory requirements as of 1976 are included in the design, and the costs include mechanical draft cooling towers. The major regional effects on nuclear unit capital costs result from differences in site labor and material costs. These costs were estimated separately and then applied on a statistical basis to determine regional cost multipliers to be applied to the cost of the reference design.

All the capital cost estimates are significantly affected by assumptions made about various time-related cost factors. The direct costs of constructing a generating unit can be well approximated; uncertainties in the cost estimates are largely a function of how well the time-related cost factors can be established. In this analysis, licensing time, construction time, construction interest rate, and contingency allowance were varied to establish the capital cost ranges. In addition, the upper end of the cost range for the western region capital cost estimates has been further increased to allow for an increased chance of greater site-sensitive costs, primarily because of the generally greater environmental and seismic sensitivities in much of this region.

Fuel cost studies

The fuel cost information developed in this study is the result of the efforts of several organizations. The MITRE Corp. and ICF Inc. developed the coal and coal transportation cost information; S. M. Stoller Corp. developed the data on uranium costs, and NUS Corp. developed the information on the remainder of the nuclear fuel cycle. This information was used by the EPRI staff to develop the delivered coal costs in the six regions and the nuclear fuel cycle costs nationwide (Table 3). Values are given for the years 1976 and 2000. The two sets of values are different, although both are expressed in 1976 dollars, as the costs of coal and of the nuclear fuel cycle are expected to escalate at a rate greater than the rate of general inflation.

The coal price estimates are based on these major assumptions:

- The prices are long-term equilibrium prices, implying that coal is a demand-constrained industry without major supply constraints other than the size of the resource base.
- There will be no major institutional constraints on western coal development.
- The overall demand for coal will not cause serious depletion problems for normal steam coal types until the post-2000 period.

The coal transportation cost estimates were based on the general application of unit trains for hauling coal to the large power stations considered in this analysis. Barge transportation was considered when this could be applied to reduce costs. Distance estimates were derived from an analysis of recent steam coal shipments to utilities, with an average distance derived from centroids of the supply and demand regions.

The levelized nuclear fuel cycle costs are made up of the cost of uranium plus the costs of enrichment, conversion, processing, fabrication, and waste disposal, with a credit for plutonium production. The cost of each of these components was first investigated separately. The costs were then combined, accounting for the timing of the required expenditures, and finally the results were levelized. Uranium resource estimates were taken from the ERDA report, *National Uranium Resource Evaluation, Preliminary Report* (June 1976). Uranium prices are expected to increase in the future at a rate significantly greater than the rate of general inflation, primarily because of resource depletion, but the other components of fuel cycle costs are expected to have a stabilizing influence, substantially moderating the overall expected escalation rate.

Other factors

The revenue requirement calculations were based on a fixed charge rate of 18%, a 10% discount rate, and a 30-year assumed life for both the coal and the nuclear units. These values are considered to be consistent with a 6% annual inflation rate.

As the difference in expected availability between coal and nuclear generating units is not expected to have a major effect on a cost comparison and is speculative at best, availability differences are excluded from the analysis. Coal and nuclear units on the same system tend to operate at different capacity factors, but in this study the same levelized capacity factor—66%—was applied to both types of units to avoid distortion of the busbar costs.

Operation and maintenance costs were estimated by the EPRI staff, based mainly on Federal Power Commission data for nuclear units and for coal units without flue gas desulfurization. Recognizing the limited experience with mature designs, operation and maintenance costs for scrubbers were estimated separately and include costs for required lime or limestone, as well as for sludge stabilization sufficient for landfill disposal.

A study such as this could include as much detail as the financial resources available for the study would allow. A point of diminishing return is soon reached, however, where the uncertainties in predicting the future overwhelm the factual data. Some uncertainty can be reduced by the analysis of specific sites, but at the loss of general applicability. This study is believed to have analyzed the principal factors in appropriate detail for a general comparison of coal and nuclear generating costs on a regional basis under current conditions.

From Bench to Busbar

Developing new technology is no assurance that application will follow. Involving the user and vendor in the R&D process from the beginning is a key to successful transfer.

EPRI's success as the R&D arm of the U.S. electric utility industry will be measured over time by how effective the Institute is in transferring the results of its research from bench to busbar.

This has been a guiding concern since EPRI's founding and led to the early creation of a network of advisory committees made up of some 350 utility people from the operations, engineering, and R&D sectors of the industry. This advisory group provides guidance and evaluation of EPRI's R&D program planning from the policy-applying Research Advisory Committee to the technology-oriented task forces working at the program level.

Essential to successful transfer of technology to commercial application, in the experienced view of EPRI President Chauncey Starr, is the involvement of the user (and the manufacturer when equipment is involved) in the R&D process from the beginning.

"No utility engineering team will use equipment it isn't familiar with," says Starr. "And no manufacturer will build and guarantee a product that it hasn't been involved in developing. There has to be confidence in the equipment or procedure," he adds. "And the way you achieve this is to make the responsible utility and manufacturing people a party to the R&D."

Lawrence Papay, director of research and development at Southern California Edison Co., and a member of EPRI's Research Advisory Committee, shares Starr's view.

"The weak link between technology development and use," says Papay, "is that in most cases those involved in R&D and in its use are not the same people."

Papay goes a step further and stresses, "It's important to the transfer and acceptance of technology that new equipment be successfully demonstrated on a utility system." Papay notes that EPRI's advisory committee organization allows for definition of utility system requirements during initial R&D phases "as a developing technology moves from laboratory to bench to demonstration, but there is still the need for a utility to prove out the technology on its system."

Typically, the cost of R&D accounts for merely a fraction of the total cost of bringing a new technology to the marketplace. The manufacturer's investment in the engineering, fabrication, and marketing of new products, as well as the cost of utility users in applying new equipment, usually far exceeds EPRI's R&D costs through the demonstration phase. The risks involved in application of a new technology can inhibit substantial industry investment unless the transition problems are recognized and dealt with early in R&D planning.

EPRI's efforts have also served to demonstrate that some innovations are not practical. More than a dozen such projects have been phased out, including work on the flywheel and superconducting magnetic energy storage.

Key factors

A survey by Richard Schulte, EPRI Planning Staff, of past studies on the problems surrounding technology transfer reveals the apparent requirements for successful commercialization of new products. Generally, the simultaneous presence of five elements is needed and their timely convergence is critical for successful technical innovation and its acceptance.

□ The R&D must be continued until all the principal technical problems are solved. Premature demonstration of a new technology can effectively block future acceptance.

□ There must be a customer in need of the product. When new technologies necessitate a search for application, successful transition to use is unlikely.

□ An advocate for the new technology must be visible and actively committed to ensuring commercialization. The advocate's role is to keep the new idea perking and to ensure that vendors, utilities, regulators, and other agencies are informed of the innovation's potential value. These agencies should also participate in the transition planning.

□ Money, manpower, fuels, and other supporting resources needed to introduce the technology must be available.

□ Economic, political, and social factors (risk factors) must be favorable to encourage private sector investment.

EPRI's approach is to take the following steps to promote transition.

The decision to proceed beyond feasibility studies of a new technology is based on at least preliminary planning for achieving transition to commercial use. An informal airing of these plans takes place during task force, division, and management reviews of the requests for project authorization.

Cofunding of specific projects by utilities and vendors is sought to indicate utility needs and to enlist vendor interest and commitment.

Where feasible, new equipment is tested on utility systems using utility people for installation, monitoring, and operation. This gives utilities early exposure to the technology and provides practical test conditions for the new equipment, fuel, or procedure.

Careful consideration is given to selecting contractors with proven ability or promising potential for bringing innovative technology from the laboratory through engineering, production, and marketing to utility use. Negotiated proprietary rights are used to enhance this transition potential.

A case study is offered to illustrate how EPRI has caused the convergence of the five elements favorable to technology transfer.

Case study

A high-intensity ionizer, designed by Air Pollution Systems, Inc. (APS) of Seattle, Washington, has been built and tested successfully at TVA's John Sevier Power Station. The compact ionizer is designed to be installed at the inlet to the precipitator on fossil-fueled power plants. It charges the particulates to about five times the level achieved in conventional precipitator stages, resulting in much higher particle collection efficiencies, even with high-resistivity ash. The ionizer may achieve a 25–30% capital cost reduction with only a slight energy loss penalty in new precipitator installations. Even larger cost savings are expected for retrofit installations.

Complete the R&D Research and testing of the ionizer is continuing to ensure that all operating features and specifications for ordering and fabricating it are known before commercial application. A prototype device is being evaluated at EPRI's Emissions Control Test Facility at the Arapahoe Station of Public Service Co. of Colorado. Separate estimates for the ionizer economics were made by Kaiser Engineers and Enviro Energy Co. to increase confidence in the anticipated economic benefits.

Define utility needs TVA is moving ahead with plans to demonstrate this technology by retrofitting its Shawnee Power Station with an ionizer. Increasingly stricter particulate control standards have created a need for the technology especially where high-resistivity ash is being discharged from existing coal-fired units.

Identify an advocate By first recognizing the potential of the device, by creating the facilities for its testing and demonstration, and by providing the funds to develop it, EPRI has served as the agent for promoting this highly effective particulate control device. EPRI has made an effort to keep utilities and manufacturers informed of the potential performance characteristics of the ionizer. By control of key patents, EPRI will ensure fair licensing of the technology to all precipitator companies. An initial license has been issued to Union Carbide Corp., which has entered into a technical and financial partnership with APS and will assist in marketing the device.

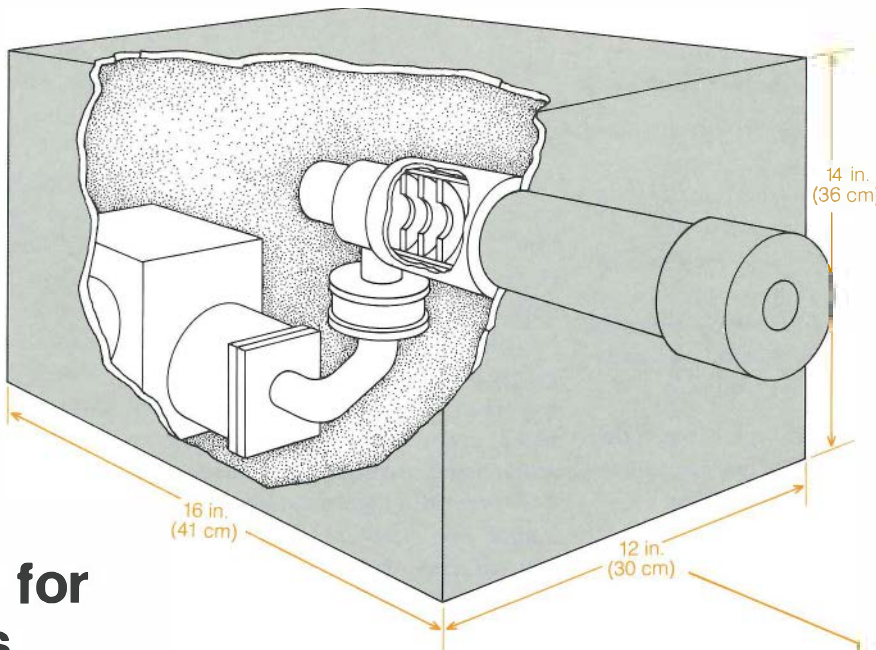
Resource availability No special materials or unusual fabrication techniques are needed to produce the ionizer. All resources necessary to build and market it are probably available at each of several precipitator companies.

Risk factors Detailed cost studies for the retrofit application at the Shawnee Station indicate that design, fabrication, and construction can be completed for $6/kW. This is but a fraction of the cost of any other kind of retrofit by conventional precipitators or fabric filters. The attractive economics and careful testing should encourage early widespread application and limit the first-of-a-kind risks.

This project was begun as a high-risk venture in 1974, with expenditures so far amounting to less than $600,000. It represents the timely convergence of a technology, a utility requirement, preplanned test facilities, a qualified research staff, and adequate funding.

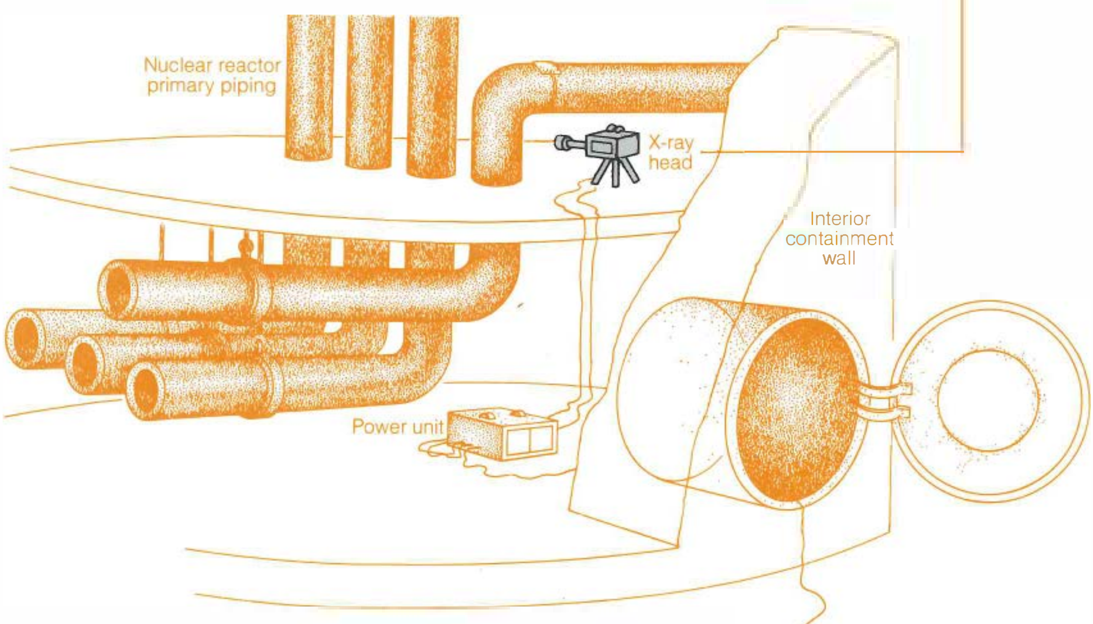
Other examples can be cited: synthetic (fly-ash–derived) power pole; advanced nuclear analytic codes; polymer-concrete insulator; compact transmission lines; and wood-pole preservative.

Since it began operations in 1973, EPRI has undertaken more than 1000 research projects and published over 400 technical reports on completed research. A thousand projects and 400 reports are of themselves only statistics. What is important was noted in the August JOURNAL by L. F. Lischer of Commonwealth Edison Co., chairman of EPRI's Research Advisory Committee: "Our real satisfaction will come as we see substantial use of the results."



Portable Radiography for Power Plants

To meet the need for X-ray inspection of interior surfaces of components and welds in cramped quarters in a nuclear plant, EPRI is developing a miniature radiography apparatus.



A portable radiography system for in-service examination in a power plant.
The heart of the system is a small X-ray head. The measurements indicate the target for the prototype.

Concurrent trends in the nuclear power industry suggest that in the future, radiography may become the most desirable method for in-service inspection of reactor components—especially those that are complex in shape or not amenable to ultrasonic inspection. These trends are the increasing size of nuclear power generating stations and the tightening of both NRC inspection requirements and industry codes, such as the ASME Boiler and Pressure Vessel Code.

Most power plants tend to be cramped and confined, and this is even more true of nuclear plants with their thick interior concrete shielding walls. It is obviously impractical to consider hauling huge components out of place in a power plant for periodic inspection, but even if it were possible, this would require cutting the very welds whose integrity needs to be verified by inspection. For these reasons, the situation appears to be a classic instance of "having to take the mountain to Mohammed"—the normally heavy and unwieldy X-ray equipment must be taken to the work rather than vice versa.

At the present time there is no portable radiographic inspection system having the energy, the size, and the weight to meet the present and anticipated needs for in-service inspection of reactor primary systems.

Development of a portable, high-energy radiographic system—compact, *truly* portable, and highly flexible for field set-up—would be most valuable for inspection of welds in large, cast stainless steel pump and valve bodies and large-diameter, heavy-wall, centrifugally cast, stainless steel piping. In June a planning meeting at EPRI identified 11 specific potential applications for such a portable radiography system. These are now being studied in detail, including determination of access requirements for the X-ray head.

- Pump body welds
- Pump support lugs
- Valve body welds
- Dissimilar metal safe-end welds
- Safe-end welds with complex thermal sleeve design
- Valve support welds
- Valve-to-valve, fitting-to-pipe, and fitting-to-fitting welds
- Control-rod-drive housing welds
- Centrifugal cast stainless steel pipe welds in primary coolant systems
- Reactor pressure vessels: confirmation of ultrasonic indications
- Secondary (nonradioactive) system piping in older plants

Project contract

EPRI awarded a contract to Southwest Research Institute (SwRI) to manage the development of the technology required to build a portable radiographic inspection system compatible with existing, mechanized inspection equipment and with LWR access and geometry (RP822). The system must be capable of doing in-service and repair inspections of both BWRs and PWRs in accordance with the existing ASME Boiler and Pressure Vessel Code; it must be manually transportable by two inspectors, and small enough to be used for external (outside surface) radiography of primary system piping down to and including the bypass lines of a BWR under most present-day access conditions. It must produce Code-acceptable radiographs through two pipe walls with the pipe containing water (film opposite source). For internal radiography (of the inside surface), the system must be small enough for the head to be placed inside the nozzles of a PWR pressure vessel (diameter ~35–40 cm, 14–16 in), producing Code-acceptable radiographs through one nozzle wall with the nozzle full of water and film placed on the outside surface.

In addition to the management contract, major subcontracts for development of the system have been let to the Stanford Linear Accelerator Center, Schonberg Radiation Corp., and the J. M. Co. In addition, a project advisory committee has been formed of consultants and a representative of Philadelphia Electric Co.

The contract covers fabrication of a laboratory prototype apparatus that can be used to verify performance of components and the overall system.

A survey carried out for EPRI by SwRI in 1975 indicated that an electron linear accelerator (LINAC) offered the best promise for development of a portable, high-energy radiographic system. The operating principle of a LINAC is analogous to surfing: a pulsed group of electrons is injected into a tuned waveguide just ahead of the crest of a microwave pulse traveling down the waveguide, thus achieving acceleration of the group of electrons. When the desired velocity is reached, the electrons are focused on a heavy metal target and X-rays are generated.

The SwRI survey indicated that many of the essential components are now available, but they require reduction in size and weight and integration into an inspection system specifically designed to meet the needs of the nuclear power industry. As Table 1 shows, the greatest reduction in size and weight is required in the X-ray head, which must be small enough to fit inside apertures in components and therefore needs to be reduced by almost an order of magnitude from what is available on the shelf today.

Three sequential tasks

The project is organized in three sequential tasks, scheduled to be completed in 3 months, 3 months, and 24 months, respectively. The first task has been completed.

Analysis of Radiographic Inspection Requirements An intensive study of LINAC design variables is being made to determine the optimal utilization of radiography for in-service and repair inspection for present and future applications in the nuclear industry. The study is to recommend size, shape, and energy level for present and near-term (2–5 years) requirements, locations where the

Table 1
REDUCTION REQUIRED IN EXISTING RADIOGRAPHIC COMPONENTS

Component	*Current Measurements*		*Target for Prototype*		*Reduction Required (%)*	
	Dimensions	*Weight (lb/kg)*	*Dimensions*	*Weight (lb/kg)*	*Volume*	*Weight*
X-ray head	29 × 28 × 66 in 71 × 70 × 165 cm	2000/900	12 × 14 × 16 in 30 × 35 × 40 cm	90/40	95	96
Power supply	83 × 48 × 30 in 215 × 120 × 76 cm	1500/680	24 × 26 × 36 in 60 × 66 × 91 cm	275/125	81[a]	82[a]
Control console	10 × 20 × 15 in 25 × 50 × 38 cm	60/27	10 × 16 × 20 in 25 × 40 × 50 cm	55/25	0	8
Heat exchanger	(integral with power supply)		18 × 18 × 24 in 45 × 45 × 60 cm	100/45	—[b]	—[b]

[a]Reduction factor applies to power supply only.
[b]Reduction factors: 75% in volume and 7% in weight for combined power supply and heat exchanger.

system will be used (which components, the piping type and size, and the like), and what radiographic techniques will be used (through two walls with water inside, through one wall from the inside, the type of film, and so on.) Reactor designs of all four LWR vendors (Babcock & Wilcox Co., Combustion Engineering, Inc., General Electric Co., Westinghouse Electric Corp.) will be considered in detail. A cost study will also be made to determine where portable radiography can be used as a supplement to, or replacement for, other techniques to improve overall inspection performance.

Alternative radiographic systems will also be investigated to determine their applicability for solving specific near-term and future (over 3 years) inspection problems.

LINAC energy levels and intensities in the range of 1.5–6.5 MeV and X-ray head diameters of 9–41 cm (3.8–16 in) will be studied.

The degree of technology development required for production of each of the various radiography systems proposed will be reviewed.

Analysis of LINAC System Requirements A detailed engineering analysis will be carried out for the optimal system configuration, weight, energy, and intensity determined in Task 1. This will include design approaches, definition of critical development items, analysis of required component and system performance, and elaboration of a comprehensive and detailed plan to develop the system selected. The plan will describe all remaining analyses, designs, and tests needed for each component of the system.

Design and Development of the Prototype System This includes fabrication of a laboratory prototype system that can be used to verify component and overall system performance and is able to be taken to a field site for radiographic evaluation. However, under the terms of the present contract the prototype need not be waterproofed or packaged for protection against radioactive contamination, as it will have to be for actual field use.

SwRI and EPRI believe that there is a high probability the project will be successful and that a prototype meeting the physical parameters established can be delivered on schedule—by the end of April 1979.

Any additional input from utilities concerning other applications, including access and space restrictions, is welcomed as an aid in arriving at optimal performance capability for the system.

Arthur Hansen: Engineering Education to Fit the Times

The president of Purdue University reports that students are eager to try solving today's complex energy and environmental problems.

□ An EPRI interview

Welcoming the 5000 freshmen at Purdue University last year, the president casually remarked that if they ever had a chance, they should feel free to stop by his house and say hello.

"About two weeks later," recalls President Arthur Hansen, "a student called me at home, saying he wanted to come over. When I asked him what he wanted, he said, 'Nothing in particular.'

"Then why are you coming over?" Hansen asked. "Because you invited me," replied the student.

As Hansen tells the story, he breaks into a broad smile. "The student came over that night and thoroughly beat me in a game of chess. It turned out he had been playing since he was six years old and was a former state champion."

Although that may be the last blanket invitation Hansen gives, the incident illustrates the type of campus atmosphere he strives to maintain.

Hansen, who also serves on the EPRI Advisory Council, is far removed from the stereotype of a university president sitting in an ivory tower, unaware of the outside world. When interviewed in his office last June, he talked at length about the critical issues facing higher education and industry.

"There are so many claims made about higher education that just don't wash. The idea that higher education is the one great thing that can solve all the problems of tomorrow is nonsense," Hansen asserts, adding that higher education is limited in the context of other social institutions.

Hansen believes that college can provide a young person with certain job skills, as well as an environment for maturation, and—ultimately—can help develop well-informed citizens capable of making intelligent decisions. "We try to provide students with an education that will help them survive social and technological changes. That is part of our educational approach," he states.

Hansen considers that a good college education consists of the transfer of skills necessary to enter a profession, the development of personal values for good citizenship and emotional stability, and a heightened awareness of the world in which we live.

Are students of today any different from those of ten years ago?

The Purdue president, who holds a doctorate in mathematics and is a former chairman of the University of Michigan Department of Mechanical Engineering, thinks that the turbulent 1960s did raise important issues in higher education, while also making faculty and administrators more aware of national problems.

"The greatest change, however, is with the students themselves," Hansen says. "I just don't see the campus leaders rallying the troops out in the square today. Students are much more cautious now about following leaders. They also have a more mature attitude toward complicated problems.

"I think that many student answers to problems set forth in the 1960s were simplistic. In fact, 'solving problems' was not even the intent of some students. Supporting a cause and having an identification with a group was probably the reason for much unrest. I think today's students are more mature in that regard. They work harder for tangible results."

While students in general may be less vocal today, critics of engineering schools are not. Many charge that engineering educators are more concerned with teaching concepts, theories, and science than with the practical art of engineering and technology.

Hansen, a thirty-year veteran of engineering education, disputes those charges, although he agrees that the space-age technologies of the 1960s were essentially geared to engineering science.

"Ten years ago," comments Hansen, "fundamental engineering was very important because of the nature of the aerospace industry and other emerging technologies. There were not, for example, any handbooks on designing a lunar landing vehicle."

The university leader acknowledges

"We try to provide students with an education that will help them survive social and technological changes. That is part of our educational approach."

that the theoretically oriented person with a PhD was the one to hire in the 1950s and 1960s. "The young assistant professor, who had never been outside the walls of the university, obtained a PhD and remained at the university to teach. It was self-perpetuation of a particular approach to education," he notes.

But this trend toward basic engineering and engineering science, Hansen asserts, did have a positive result. "It enabled a person to change as technology changed, be it electronics today or solid-state physics tomorrow. He knew the chemistry, the math, and the basic sciences, and therefore he was able to move in wholly new directions."

Hansen believes it is wiser to concentrate on the basics than on the routine applications because the routine applications can be quickly learned by most students. He does feel, however, that a good balance exists now between basic and applied engineering education at most universities.

Art Hansen, who is only the second engineer to serve as Purdue's president in the university's 104-year history, also has strong opinions on the relationship between higher education and industry. As a director of several large corporations, he is familiar with this subject. In his conversations with educators and industry executives, he often stresses the importance of universities' staying in touch with industry.

"In one sense, industry is our customer," he states, adding that if a university turns out students who cannot get jobs or perform satisfactorily on the job, this naturally reflects on the institution.

A NASA research scientist prior to his affiliation with the University of Michigan, Hansen believes that the energy industry is beginning to assume the same "glamour" that the aerospace industry once had. A critical problem right now, he says, is for universities to meet the unprecedented demand for qualified energy engineers.

"Purdue is very sensitive to industry's

need for technical people trained in the energy disciplines," he notes, adding that Purdue has a strong power engineering program.

Indeed, according to a 1973 report prepared for the National Science Foundation, *Assessing the Impact of Changes in National Priorities on the Utilization of Scientists and Engineers in the 1970s*, the number of engineers needed to meet accelerated domestic energy production could increase from about 100,000 in 1970 to 225,000 by 1985.

As an example of the student interest in energy, Hansen points to Purdue's new public policy program and Energy Engineering Center, where research and training on energy policy will be conducted. He explains that the idea of the center is to allow graduate students from the social sciences, for example, to work toward a master's degree in public policy by taking additional courses in technology or business. Technical students, in turn, are required to take courses in the social sciences.

"Through the center, students gain a broad understanding of energy issues, which can be used in public policy matters of industry and government," states Hansen. He says these students could be employed as objective third parties in energy disputes.

"Graduates from the center could address an issue, like the safety of the breeder reactor, in an unbiased way, with no ax to grind," he comments.

Hansen stays in touch with the energy research community through his position at Purdue and through memberships on the advisory councils of EPRI and the Gas Research Institute.

How supportive does he believe the Carter Administration will be of university research? When President Carter first took office, he met with a select group of educators to discuss research support. Hansen concedes he was somewhat disappointed, although he hesitates to make any final judgments.

"I would say the issue is still an open one, but there are no positive signs that university research will improve under the new administration," he remarks.

"I just don't see the campus leaders rallying the troops out in the square today. Students are much more cautious now about following leaders."

Although Hansen does voice reservations about the administration's energy program, he applauds President Carter for helping to make the energy problem clear to the American public. As for the program itself, Hansen is unsure whether the nation can move toward a coal economy as quickly as the president hopes it will. Institutional barriers are formidable.

Understanding the energy field today is very difficult at times, he admits. He says, for example, that comprehending the many facets of the EPRI program is very hard unless one knows all the reasons that led to specific decisions in the program planning. In answer to criticism that EPRI should take some cues from the outside rather than entirely from the electric utility industry, Hansen feels this is where the EPRI Advisory Council can be valuable.

"One of the main reasons EPRI exists is to provide a program of research that will benefit the ratepayer. For that to happen, the utility industry has to identify the problems and determine how to implement solutions. I really think the industry is better able to do this than any other group.

"The Advisory Council is important because we represent a cross section of citizens and can question whether an adequate return to the ratepayer is resulting from EPRI's research."

What does a university president do in his spare time? Hansen says when he is not busy running the West Lafayette, Indiana, campus or getting trounced in a game of chess, most evenings are spent at student or faculty affairs. "Being with the students and faculty is something my wife and I find very pleasurable, so we try to do as much of that as possible," he says.

It is precisely that tireless interest in people that one first detects when meeting Hansen—an interest that extends itself to institutions and systems as well as people. He readily admits that he has an insatiable curiosity for trying to figure out how institutions and systems work. In short, the university president clearly projects the image of a man who would rather be interviewing than be interviewed.

One area that especially intrigues him is political science, which, he says, he knows little about.

"I have been spending much of my free time reading about the political history of the United States. I'm interested in better understanding how this country came into being. What, for example, are the foundations of a democracy? How do political systems evolve? What are the underlying philosophies that undergird democracies and other types of governments?"

As a member of the board of trustees for the National Fund for Minority Engineering Students and as a former chairman of the National Research Council Committee on Minorities in Engineering, Hansen is aware of some of the problems inherent in making a democracy work.

He concedes that there are very few women or minorities in the engineering fields but notes that the situation is rapidly changing, at least for women.

"At the present time, about 10% of all women enrolling as freshmen at Purdue are enrolling in engineering schools—an astounding figure," he remarks, "when compared with the past."

According to Hansen, the problem in attracting minorities to the engineering field is more complex than it is with women.

"Long-standing problems—problems that go way back to high school—hit you when you're dealing with minorities in engineering," Hansen states. "There is a lack of role models, which, of course, is also true with women, but it is much more dominant with minorities."

"Instead of wondering how the engineering student can become a 'whole person' without taking course offerings in nonengineering fields, it might be better to ask how the nonengineering student can become a 'whole person' without taking courses in technology."

Hansen points to the "defective preparation and counseling" in many inner-city high schools, which tend to steer disadvantaged students away from engineering schools.

While the National Fund for Minority Engineering Students is trying to alleviate the scholarship aid problem for many students, Hansen explains that the National Research Council Committee on Minorities in Engineering deals with program development. The university president notes that such programs range from high school counseling and curriculum development to the retention of minority students once they enter an engineering school.

"The committee on minorities tries to assist students all the way from high school to an engineering position after college," says Hansen. "One hopes that we will eventually attract more minorities into engineering, including the electric utility industry."

As for the role of engineering education in our society, Hansen says that every student should have a basic knowledge of technology. "And instead of wondering how the engineering student can become a 'whole person' without taking course offerings in nonengineering fields, it might be better to ask how the nonengineering student can become a 'whole person' without taking courses in technology."

At the Institute

Fusion Agreement Signed With Soviet Research Group

An agreement between EPRI and the Kurchatov Institute of Atomic Energy in Moscow was signed recently for an energy research program investigating the use of fusion power to produce fuel for conventional nuclear power reactors.

The agreement provides for the establishment of a joint U.S.–USSR working group to plan a program for testing U.S.-built modules during a major Soviet fusion demonstration experiment now being designed. Extension of the agreement will be required before funds are committed.

Unlike fission, where a heavy atom is split into two lighter ones to release energy, fusion occurs when two light atoms unite and form a heavier one, releasing energy in the same way as do the sun and the stars.

The fusion project is geared to the fusion-fission hybrid concept, a combination of fusion and fission technologies. EPRI studies have shown that the hybrid concept is an extremely effective fuel factory for fission reactors.

In essence, a fusion reactor would be nested inside a hollow fission blanket, like a box within a box, so that the plentiful neutrons produced in the inner part can be used to breed fissile material, such as uranium-233 or plutonium, and, if desired, to produce power by fission in the outer part. The fusion conditions necessary for such applications are significantly less stringent than for a fusion system designed solely to produce electricity. Such hybrid plants could also be designed to transmute highly radioactive waste from nuclear power plants into less hazardous materials that are more easily stored.

The fusion power reactor concept that is receiving the most attention in the U.S. and USSR is the Soviet tokamak. Both countries will have experimental tokamaks operating by the 1980s, although the design and size of the two machines will differ.

The Soviet tokamak, the T-20, will be larger than the tokamak fusion test reactor under construction by ERDA at Princeton University. Unlike the U.S. tokamak, the Soviet machine is being designed as an engineering test of the hybrid concept. According to EPRI officials, there is no other fusion machine under design that could evaluate the concept of extending our fission fuel reserves by using fusion neutrons.

The joint EPRI–Kurchatov program may lead to sending a U.S.-designed and -built module to the USSR for testing on the T-20. This module would test neutron absorption characteristics and would be designed to produce plutonium or uranium-233. The power distribution in the module would be measured and energy extracted with a coolant, as in a power plant.

The program allows U.S. fusion researchers to gain some firsthand experience in evaluating fusion-fission reactors at an early date. According to William Gough, manager of EPRI's Fusion Program, the Soviet Union has defined fusion-fission reactors as the near-term goal of their fusion program. This agreement marks the first commitment by a U.S. organization to consider an experimental examination of the concept.

"The program is part of a number of EPRI studies under way to determine the advantages and disadvantages of fusion-fission energy systems and how soon the U.S. might expect such systems to be ready commercially," says Gough. He notes, however, that fusion power, whether for electricity or for other purposes, will take many more years of research and development.

Fusion-fission fuel factories could be very attractive to the electric utility industry in the future because of their effectiveness in producing fuel. This is especially true if uranium supplies needed for today's nuclear fission reactors run short in the future.

Gough termed the whole idea of using nuclear fusion to produce both fuel and electricity as an "interesting alternative" to current U.S. fusion efforts, which are primarily geared to fusion development purely for electricity.

Thesaurus and Index Available

Two publications, recently developed by EPRI staff, will help those working in the electric utility industry, both in writing reports, and in identifying reports already published.

A Thesaurus of Electric Utility Industry Terms, prepared by the RDIS Project Office, supplies a vocabulary of terms used in the EPRI Research and Development Information System (RDIS), which contains information on in-progress R&D projects of the U.S. electric utility industry. It is revised yearly.

A Permuterm Index of Keywords in Titles of Published EPRI Reports, prepared by EPRI Librarian Laura Henning, contains all keywords in titles of numbered reports and is updated monthly.

The publications may be obtained by contacting the EPRI Publications Administrator.

EPRI Sponsors Data Bank

EPRI and members of the nonferrous smelting industry are sponsoring an air pollutant health effects data bank with Arthur D. Little, Inc. (ADL) of Cambridge, Massachusetts (RP331).

The scientific data bank includes extensive information on the effects reported in humans, animals, and plants from exposure to sulfur oxides, ozone, nitrogen oxides, lead, cadmium, arsenic, and particulates. The number of references in the data bank is approaching 7000. The largest file, that on sulfur oxides, contains more than 2600 citations. While most papers concern the effects of sulfur oxides on humans, animals, and vegetation, some 100 references deal with atmospheric chemistry, acid precipitation, and urban concentrations.

The data bank is continuously updated to include the latest information from both domestic and foreign sources. Data are collected through computerized literature searches packaged by Bibliographic Retrieval Services, Lockheed Missiles & Space Co., Inc., and System Development Corp., with access to the MEDLARS, BIOSIS previews, and CAIN (National Agricultural Library) data bases.

Some 70 scientific journals are reviewed manually in addition to a number of indexed bibliographies, including *Biological Abstracts, Chemical Abstracts, Current Contents, Excerpta Medica, Index Medicus*, and NTIS weekly government abstracts.

In addition to reviewing the published literature, trained ADL staff members attend appropriate scientific meetings and interview scientists conducting research in areas of interest. The data bank is used by ADL staff in responding to specific questions posed by the sponsoring organizations.

During the six years since its inception, the data bank has proved to be an effective source of information for evaluating scientific publications, preparing the scientific background for legal briefs, and analyzing toxicological studies of laboratory animals and environmental studies of humans in both industrial and urban surroundings.

The information system is available at no cost to EPRI members. A brief but appropriately detailed description of a problem, a listing of the information needed, and a comment on how the information will be used should be sent to Harry A. Kornberg, EPRI Environmental Assessment Department.

It is recommended that requests for such information be made well in advance of the time the information is needed since ADL will need time to assemble, organize, interpret, and critique the scientific literature. Reports prepared under this arrangement become available to other members of the industry and to the public.

A utility may arrange directly with ADL for similar but private use of the data bank. Under these conditions, and within the contractual agreements with ADL, disposition of the resulting report would be at the discretion of the utility. Because of EPRI's tax-exempt status, in this case the utility would bear the full cost of the service.

Solution Proposed to Breeder Dilemma

A solution to the nation's breeder reactor dilemma—one that would meet objections based on fear of nuclear weapons proliferation and still permit development of the breeder as a virtually inexhaustible energy supply—was proposed recently by Milton Levenson, director of EPRI's Nuclear Power Division, in testimony before the U.S. Senate Subcommittee on Energy Research and Development.

The key point of the proposal is to throw overboard the unwarranted assumption that the traditional Purex process is the only spent-fuel reprocessing method that should be considered for breeders. (This process, developed in the WWII Manhattan Project to isolate weapons-purity plutonium, involves dissolving the fuel in an acid solution and chemically separating out the fission-product wastes to leave pure plutonium and unfissioned uranium.)

Early work (1955–1965) on LMFBR fuel cycles did not envision use of a Purex-type process, and the first experimental breeder to have its fuel reprocessed (EBR-II) used a nonaqueous, pyrometallurgical process that only partially decontaminated the fuel. It completed reprocessing and refabrication in a 30-day cycle and returned to the reactor "new" fuel that was as proliferation-resistant as spent fuel—that is, it required remote handling behind heavy shielding.

Pyrometallurgical processes are not the only technology that can provide a fuel cycle with significant proliferation resistance, Levenson told the subcommittee. A simpler approach is a modified Purex-type process that contains only one cycle of purification instead of two or three so that significant amounts of radioactive waste remain with the fuel, wherein uranium is not completely separated from plutonium. This would produce a fuel essentially as difficult to use as starting material for illegal weapons production as ordinary spent fuel, because it would still require elaborate processing before it became suitable for use as an explosive.

Such a modified Purex process, as proposed by Levenson, has two advantages over other methods proposed for denaturing fuel by adding highly radioactive materials to make the material useless as bomb material. One is that the material is never produced in a weapon-usable form, not even internally at a secure site. The second advantage is that a possible national change of nuclear weapons policy by the country with such a facility could not suddenly result in bomb material becoming available by the simple expedient of not denaturing.

An important contributory factor to today's dilemma, Levenson declared, was the decision in the mid-sixties to stop all research on alternative breeder fuel cycles in order to concentrate available funds on the reactor itself. "With the benefit of hindsight, this seems to have been an error, but it need not be a fatal error," he said. He asserted that reactivated development on breeder fuels and fuel cycles in parallel with development of the reactor would lead to a system by the mid-nineties that "would have acceptable proliferation resistance and could be commercialized if the need is there—if the need is not there, it will have been very cheap insurance for the energy security of our country."

Another reason for carrying out such a research program is that smaller countries, which are contemplating their energy needs and breeder policy, face a choice limited to traditional Purex reprocessing or nothing—"a somewhat tense situation," Levenson observed.

"If the U.S. were to proceed to develop a fuel and fuel cycle considerably more acceptable to policymakers and offer this third alternative to these countries or for use in international nuclear fuel processing centers, we could probably achieve our nonproliferation objectives and regain U.S. leadership in the world nuclear community."

"It is important to note," Levenson emphasized to the subcommittee, "that at this time there is no reasonably assured, essentially inexhaustible and substantial energy supply other than the fast breeder reactor."

None of the alternative reactor concepts being proposed to meet proliferation objections are actual breeders, and therefore they cannot provide national energy stability by providing an essentially inexhaustible energy supply. Because we are already in 1977, actual commercialization of any alternative concept cannot be done in time to extend our uranium resources significantly before the next century.

"If a commitment to proceed were made tomorrow, it would probably be 15 years before the first large-scale experimental plant could be made operational," Levenson warned. "Assuming 2 years of operation and then 10 years to build, the startup of the first semicommercial plant would be in 2004."

Assessments of alternative fuel cycles based on uranium-233 usually ignore the fact that ^{233}U does not exist in nature, nor is any supply being produced at this time. Consequently, the only options are to start up such alternative systems with either plutonium or highly enriched ^{235}U on a 20–30-year startup cycle. "It isn't clear what safeguard objectives we achieve by such a scheme, but what is clear is that two fuel cycles and two reprocessing concepts rather than one fuel cycle would have to be developed to go with the new reactor concept."

Levenson recalled a celebrated analysis of conceptual systems by Admiral H. G. Rickover in the early days of nuclear power. Said Rickover, who built the nation's first prototype power reactor as well as its nuclear navy:

"An academic reactor or reactor plant almost always has the following basic characteristics: it is simple; it is small; it is cheap; it is light; it can be built very quickly; it is very flexible in purpose; it requires very little development; it is in the study phase–it is not being built.

"On the other hand, a practical reactor plant can be distinguished by the following characteristics: it is being built; it is behind schedule; it is requiring an immense amount of development on apparently trivial items; it is very expensive; it takes a long time to build because of the engineering development problems; it is large; it is heavy; it is complicated."

Although this was written in 1953, Levenson commented, it is not only true for 1977 reactor concepts but also appears to be true for all advanced sources of energy.

A stable and assured supply of energy is so essential to U.S. safety and security that we cannot afford to be satisfied with a single energy source. "If we had converted all our production of electricity to oil in the sixties," Levenson noted, "the embargo of 1973 would have been a national disaster."

Therefore, in addition to conservation and various new but unproven energy sources, we must continue development of the LMFBR. If we pursue a vigorous program, according to Levenson, it might be possible to complete the Clinch River demonstration breeder by 1984 or 1985, to complete a large-scale experimental power plant by 1990, and the first full-scale prototype of a commercial line by 1995–2000. Delays and stretchouts of even a few years move the decision date for deployment into the next century. "In any case, the so-called breeder plutonium economy is definitely not an issue for this country in this century."

The timing for other countries is different. As few have the equivalent of our reserves of coal, oil, gas, or uranium, they are motivated to move faster on the breeder, Levenson pointed out.

We cannot say that some presently unknown source of energy may not be found sometime. But this hope is certainly too tenuous to be used as a basis for national planning and national security.

The concepts of low energy growth or even zero growth have been used to counter the argument for need for the breeder, but significant restrictions on fossil fuel availability or use could require substantial expansion of nuclear power for replacement power aside from any growth in demand, Levenson said. Nuclear power can be called the last resort because it *is* possible, *is* expandable, and is the true swing supply. As a frame of reference, if the depleted uranium already in storage at our enrichment plants were burned in LMFBRs, it would provide more than 100 years' worth of power at today's rate of energy use without requiring a single additional pound of uranium to be found or mined.

But no significant fraction of this vast resource will be available in this century.

"We are not on the threshold of commercializing the LMFBR," Levenson declared. "We are really on the threshold of deciding whether we want to develop the option, so that a deployment and/or commercialization decision can be made around the turn of the century, if the energy is needed at that time."

Culler Selected to Be New EPRI President

Floyd L. Culler, Jr., deputy director of Oak Ridge National Laboratory, will be the next president and chief executive officer of EPRI. The appointment was announced September 16 in Palo Alto, California, by the EPRI Board of Directors. Culler will join EPRI as executive vice president on January 1, 1978, prior to becoming its second president at EPRI's annual board meeting on May 4, 1978.

At that time Culler will succeed Chauncey Starr, the founding president of EPRI, who will become vice chairman of the Board of Directors on a full-time basis.

Culler has been recognized nationally and internationally for his leadership in energy research and development, particularly in nuclear power, and for his contributions in such areas as nuclear fuel reprocessing and waste management.

He has been a member of the Oak Ridge National Laboratory staff since 1947. The laboratory, one of the nation's largest federal multipurpose research and development installations, is operated for ERDA by Union Carbide Corp.'s Nuclear Division. Culler came to Oak Ridge in 1943 as a chemical engineer. He was a section chief and then director of the laboratory's Chemical Technology Division from 1953 to 1964, before being appointed Assistant Director for Nuclear Technology and then Deputy Director of

ORNL in 1970. During 1973 he served as Acting Director of the laboratory.

In 1974, he was elected to the National Academy of Engineering in recognition of his role in U.S. development of nuclear power and particularly for his chemical engineering contributions to the establishment of the nuclear fuel cycle.

Culler is a fellow of the American Nuclear Society (ANS) and the American Institute of Chemists. He received the E. O. Lawrence Memorial Award (1965), the Atoms for Peace Award (1969), and the Robert E. Wilson Award of the American Institute of Chemical Engineers (1972).

In June, along with colleagues at ORNL, he was honored with the ANS Special Award for outstanding contributions to the nuclear fuel cycle.

Culler has participated in numerous public and government activities, among them service as the U.S. representative on the Scientific Advisory Committee of the International Atomic Energy Agency and as a member of EPA's Advisory Council on National Air Pollution Research and Development.

This year, he was a member of ERDA's Liquid Metal Fast Breeder Review Committee. He has also served as deputy chairman of the panel on energy supply delivery for the National Academy of Sciences–National Research Council–National Academy of Engineering Committee on Nuclear and Alternative Energy Systems (CONAES).

Culler has been very active in civic affairs in Oak Ridge. He served as the first chairman of the Oak Ridge Planning Commission from 1956 to 1963. In 1963, he received the Oak Ridge Columbus Award for outstanding civic service contributions. In 1974 he was given the Outstanding Achievement Citation by the Engineering and Technical Community of Knoxville-Oak Ridge.

Project Highlights

Power Plant Siting May Be Eased

A $1.1 million development contract with the Linde Division of Union Carbide Corp. may ease the siting problems of power plants.

Under this contract, Linde will continue work on a new, less-expensive dry-cooling system. According to the EPRI project manager for this development, John Maulbetsch, dry-cooling systems do not need to evaporate water to cool, but currently they are very expensive systems.

"The development of an economical dry-cooling system would allow utilities to bypass the requirement to be near water and would therefore reduce siting delays," Maulbetsch said.

The capital cost for a wet-cooling system for a 1000-MW plant is $15–$20 million, while an equivalent dry-cooling system costs $60–$70 million. The higher cost primarily reflects the extra hardware involved, particularly the heat exchanger.

"The new Linde concept may cost only twice as much as conventional dry cooling," he stated.

Union Carbide, whose contract extends through December 1979, is studying the use of ammonia instead of water in the closed-loop cooling system. The ammonia boils in the power plant steam condenser and condenses in the cooling tower, thus carrying the reject heat more cheaply than the closed water system. Because the ammonia system would evaporate and condense rather than heat and cool, it could approach more closely the cooling-air temperature.

"High-performance metallic heat transfer surfaces also are being considered and could lead to lower-cost cooling systems because of low-cost fabrication and assembly," explained Maulbetsch.

Although wet-cooling systems have proved to be the cheapest and most efficient systems so far, the continuing search for plant cooling water will become more difficult in the future.

Researchers to Further Identify Pollutants

A new EPRI study will help electric utilities identify which pollutants from fossil-fired power plants may be harmful to human health.

"Through this project, scientists may be able to further identify which power plant pollutants are potentially harmful," said EPRI Project Manager James McCarroll, M.D.

McCarroll, a staff member of the EPRI Environmental Assessment Department, noted that certain pollutants now being vigorously controlled may not, in fact, be major health hazards. On the other hand, there may be other pollutants that require stronger controls. The EPRI research will help provide information for federal and state governments to use in setting environmental standards.

The study will be conducted through the University of Arizona's Toxicology Program. Researchers will investigate how airborne particulates may affect one of the major defense mechanisms in the human lung: pulmonary alveolar macrophages.

McCarroll explained that macrophages are one of the most important defenses that human lungs have against infection and destruction. Macrophage cells wander throughout the lungs, search out foreign materials—bacteria or particulates—and engulf them.

Once the cells are full of foreign materials, they ride up on a mucous blanket, propelled by cilia, and are either coughed out or swallowed and disposed of through the intestinal tract.

A major emphasis of the EPRI study is to determine what happens to macrophages when they ingest toxic particulates, such as acidic sulfate and nitrate compounds. In addition, project researchers will evaluate to what extent toxic particulates destroy macrophages and lead to the injury of lung tissue.

This particular study, according to McCarroll, is one of many under way at EPRI for assessing the environmental effects of electric power production and distribution.

EPRI Negotiates 68 Contracts

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
Fossil Fuel and Advanced Systems Division				
RP422-2	Power Plant Waste Heat Rejection, Using Dry-Cooling Towers	37 months	1112.3	Union Carbide Corp. *J. Maulbetsch*
RP545-2	High-Temperature Ceramic Heat Exchanger	11 months	349.8	Airesearch Manufacturing Co. of California *R. Richman*
RP547-3	Utility System Interface With Fusion Reactors	2 years	241.4	Bechtel Corp. *N. Amherd*
RP547-4	Utility System Interface With Fusion Reactors	2 years	300.0	Los Alamos Scientific Laboratory *N. Amherd*
RP580-2	Low-Salinity Hydrothermal Demonstration	9 months	4565.0	San Diego Gas & Electric Co. *V. Roberts*
RP734-2	Acoustic Emission and Vibration	18 months	48.1	New England Power Service Co. *D. Anson*
RP784-2	Detailed Design and Evaluation of Advanced Flue Gas Desulfurization Processes	8 months	408.3	Foster Wheeler Energy Corp. *S. Dalton*
RP920-2	Magnetic Fusion Assessment Council	7 months	1.2	K. A. Brueckner & Associates, Inc. *B. Scott*
RP922-1	Definition and Conceptual Design of a Small Fusion Reactor	2 years	425.0	ERDA *F. Scott*
RP922-3	Definition and Conceptual Design of a Small Fusion Reactor	2 years	100.0	Pacific Gas and Electric Co. *F. Scott*
RP928-4	Hydrocarbon Expander Turbine Design	3 months	24.9	C. F. Braun & Co. *G. Underhill*
RP982-5	Downflow Scrubber Design Review and Evaluation	6 months	9.9	Radian Corp. *T. Morasky*
RP983-2	Evaluation Support for Development of CONAC	1 year	20.0	Science Applications, Inc. *O. Tassicker*
RP1035-1	Fuel and Combustion Additives for Boilers	1 year	49.9	Battelle, Columbus Laboratories *J. Dimmer*
RP1042-1	Assessment of Fuels for Power Generation by Electric Utility Fuel Cells	7 months	150.0	Arthur D. Little, Inc. *E. Gillis*
RP1043-1	Evaluation of SURMAC —An Advanced Fusion Fuel Concept	18 months	400.0	University of California at Los Angeles *F. Scott*
RP1088-1	Load Leveling on Industrial Refrigerated Systems	25 months	92.2	University of South Florida *Q. Looney*

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
Nuclear Power Division				
RP308-3	Wind Field and Tornado-Generated Missile Trajectories	1 year	36.4	TRW, Inc. *G. Sliter*
RP308-10	Project Management/ Consulting Services	13 months	35.9	Botan and Redmann *G. Sliter*
RP497-5	Neutrography of Quad Cities Rods	14 months	73.7	General Electric Co. *B. Zolotar*
RP504-2	Residual Stress Measurement in Thick Metal Sections	19 months	260.2	Battelle, Pacific Northwest Laboratories *K. Stahlkopf*
RP506-5	Evaluation of Advanced Enrichment Techniques	8 months	39.0	Airesearch Manufacturing Co. of California *M. Lapides*
RP620-20	PLBR Design Studies	8 months	1150.0	General Electric Co. *J. Duffy*
RP620-22	Prototype Large Breeder Reactor Design Studies	6 months	3550.0	Atomics International Division, Rockwell International Corp. *J. Matte*
RP699-1	PWR Steam Side Chemistry Follow Program	19 months	498.1	Westinghouse Electric Corp. *L. Martel*
RP885-1	Distribution and Maintenance of Nuclear Computer Codes	18 months	556.5	Technology Development Corp. *B. Zolotar*
RP885-2	Distribution and Maintenance of Nuclear Computer Codes	5 months	15.0	Science Applications, Inc. *B. Zolotar*
RP892-1	Ultrasonic Systems Optimization Study, Project I, UT Systems Development	19 months	823.0	Southwest Research Institute *E. Reinhart*
RP892-7	Preliminary Activities—Ultrasonic Optimization Project	3 months	10.0	General Electric Co. *E. Reinhart*
RP894-3	Limiting Factor Analysis of High-Availability Nuclear Plants	16 months	347.0	Babcock & Wilcox Co. *R. Swanson*
RP895-1-4	Power Shape Monitoring System, Task 3	21 months	1120.8	Exxon Nuclear Co., Inc. *F. Gelhaus*
RP896-1	Damage and Integrity Aspects of Safety in Nuclear Plant Subjected to Creep and Fatigue	1 year	60.0	U.S. Nuclear Regulatory Commission *T. Marston*
RP956-1	Critical Flow Testing at Marviken, Sweden	42 months	800.0	Studsvik Ab Atomenergi *T. Fernandez*
RP971-2	Fuel Rod Mechanical Performance Modeling, Task 3	3 years	630.0	Entropy Limited *T. Oldberg*

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP1021-1	Thermal Anneal of Neutron-Embrittled Reactor Vessel Materials	40 months	1008.4	Westinghouse Electric Corp. *T. Marston*
RP1023-1	Small-Specimen Fracture Mechanics Analysis	2 years	200.0	SRI International *T. Marston*
RP1025-1	Neutron Dosimetry Calculations in the Vicinity of Surveillance Capsules of LWRs	1 year	57.1	Radiation Research Associates, Inc. *F. Rahn*
RP1026-1	An Experimental Investigation of the Power Ramp Performance of Standard Type PWR Fuel Elements	21 months	351.0	Studsvik Ab Atomenergi *G. Thomas and A. Roberts*
RP1067-1	Analysis of Steam Chugging in Pressure Suppression Systems	10 months	149.0	Jaycor *J. Sursock*
RP1070-1	Microstructural Evaluation of Pipe Weld Specimens Removed From Service	1 year	95.0	Battelle, Columbus Laboratories *R. Smith*
RP1071-1	Explosive Welding for Fabrication and Repair of Nuclear Materials and Components	6 months	48.0	Battelle, Columbus Laboratories *R. Smith*

Electrical Systems Division

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP68-4	UHV Transmission	1 year	100.0	U.S. Department of Interior *F. Young*
RP430-2	Bipolar HVDC Transmission System Study Between ±600 kV and 1200 kV	31 months	790.4	Institut de Recherche de l'Hydro-Quebec *L. Svensson*
RP669-2	Light-Triggered Thyristors for Electric Power Systems	18 months	344.2	General Electric Co. *N. Hingorani*
RP997-1	Determination of Synchronous Machine Stability Study Models	33 months	238.1	C. A. Parsons & Co., Ltd. *P. Anderson*
RP997-3	Determination of Synchronous Machine Stability Study Constants	34 months	173.7	Power Technologies, Inc. *P. Anderson*
RP1048-6	Advanced Techniques and Strategies for Economic Dispatch	21 months	116.8	Boeing Computer Services, Inc. *C. Frank*
RP1049-1	Research to Develop Cathodic Protection Guidelines to Mitigate the Corrosion of Copper Concentric Neutral Wires of URD Cables	3 years	85.0	Pacific Gas and Electric Co. *W. Shula*
RP1096-1	Imbalanced Longitudinal Dynamic Loads in High-Voltage Transmission Lines	17 months	98.3	University of Wisconsin at Madison *M. Silva*
RP1096-2	Longitudinal Loading Tests on a Transmission Line	18 months	38.6	GAI Consultants, Inc. *M. Silva*

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP7857-1	Increasing Ampacity Rating of Cable Termination	30 months	119.0	G&W Electric Specialty Co. *J. Piscioneri*
RP7861-1	Thermal Resistivity/Soil Stability Measuring Instrument	2 years	354.9	Ontario Hydro *T. Rodenbaugh*

Energy Analysis and Environment Division

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP860-1	Plume Conversion Rates in the SURE Region	16 months	600.0	Battelle, Pacific Northwest Laboratories *C. Hakkarinen*
RP860-2	Plume Conversion Rates in the SURE Region—Continuous Tracer Monitoring	4 months	19.7	Science Applications, Inc. *C. Hakkarinen*
RP862-2	Sulfate Regional Experiment (SURE)	37 months	4445.8	Environmental Research & Technology, Inc. *R. Perhac*
RP862-3	SURE Research Project; Aircraft Sampling Program	2 years	328.7	Meteorology Research, Inc. *R. Perhac*
RP862-4	SURE Contract; Aircraft Sampling Program	2 years	208.3	Research Triangle Institute, Inc. *R. Perhac*
RP864-1	Analysis of Dynamic Aspects in International Energy/Gross National Product Relationships	29 months	100.0	Resources for the Future, Inc. *R. Riley*
RP947-1	Battery Industry Anticipated Supply Characteristics	14 months	68.3	SRI International *R. Urbanek*
RP947-2	Battery Industry Anticipated Supply Characteristics	14 months	80.5	Charles River Associates Inc. *R. Urbanek*
RP952-1	Supply of Fuels as Influenced by Transportation	11 months	169.6	Bechtel Corp. *R. Riley*
RP1000-1	Sulfate Formation in Oil-Fired Power Plant Plumes	28 months	325.0	Brookhaven National Laboratory *C. Hakkarinen*
RP1003-1	Lung Response to Inhaled Particulates	2 years	65.0	University of Arizona *J. McCarroll*
RP1055-1	Energy Supply and Demand Properties From Engineering Process Models	1 year	90.0	Industry Studies Program *R. Riley*
RP1057-1	Polynuclear Organic Matter (POM) From a Coal-Fired Power Plant —A Comparative Study	1 year	100.0	Oak Ridge National Laboratory; Union Carbide Corp. *R. Perhac*
RP1064-1	Effects of Electric Fields on Plants and Developing Embryos	6 months	91.6	Westinghouse Electric Corp. *H. Kornberg*
RP1111-1	Assessment of Power-Plant-Induced Mortality on Fish Populations	14 months	26.0	University of Rhode Island *R. Goldstein*
PS3456-1	Assessment of Agricultural Applications for Kansas Utilities Desulfurization Solids and Ash	9 months	72.8	Midwest Research Institute *H. Kornberg*

Researchers Study Air Pollution Sources

Hundreds of researchers, using monitoring equipment from 54 ground stations and 4 airplanes, will be working in the Northeast over the next three years to learn more about the sources of air pollutants, especially one class of pollutants called sulfates.

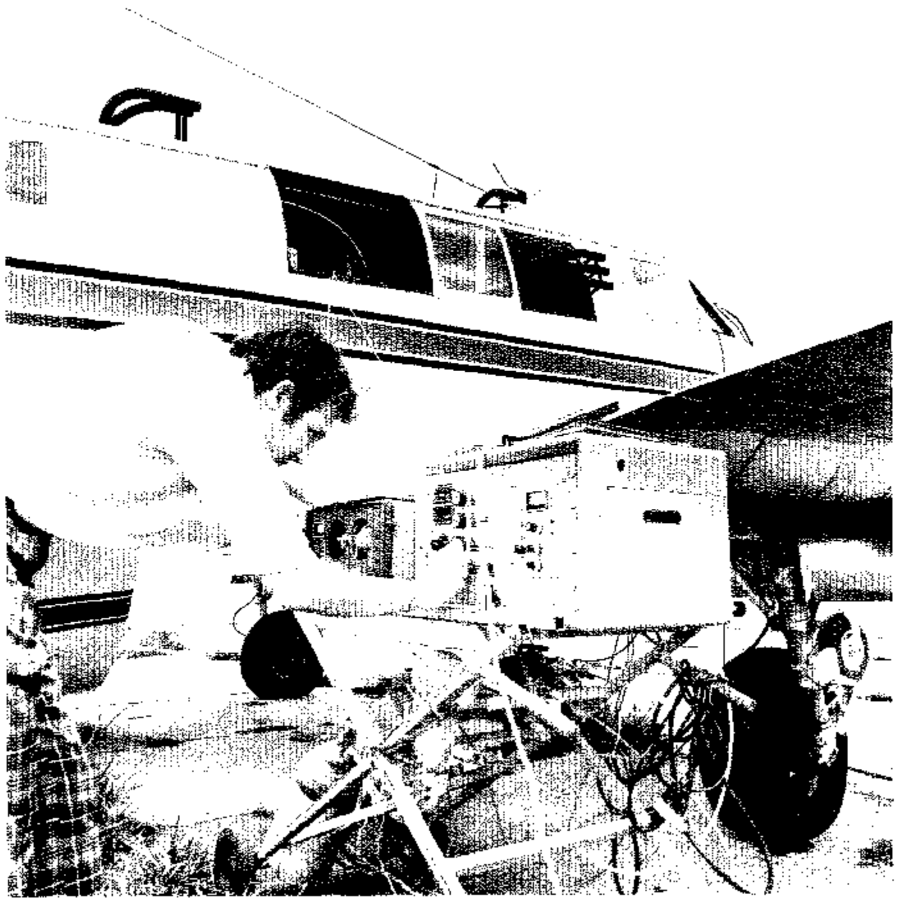
The $6.2 million research effort, sponsored by EPRI, is taking on added importance with the recent emphasis on coal for electricity production.

Sulfur in the atmosphere exists in various chemical forms and comes from many sources, including coal burning. Some sulfur forms may react in the air with other substances to form sulfates, believes Ralph Perhac, who is in charge of the EPRI project.

Until recently, scientists had focused their attention on sulfur dioxide as a possible health hazard, although sulfates are now thought to be more of a potential hazard. According to Perhac, a problem exists in trying to devise methods of controlling sulfates because it is not known exactly how they are formed or transported.

The federal government is likely to implement sulfate standards within the next few years and the EPRI study, reports Perhac, will be helpful in establishing those standards.

Donald Blumenthal, an investigator for Meteorology Research, Inc., performs a preflight instrument calibration check as part of a major EPRI project to learn more about pollutants, especially sulfates, through ground and air monitoring.



As part of the study, called the Sulfate Regional Experiment (SURE), researchers will use monitoring equipment to take daily readings of sulfur dioxide and sulfate levels throughout the northeastern United States, while also trying to estimate the emission contributions from various sources, such as power plants, industry, and automobiles. The study will concentrate on the northeastern states because that region generally has the nation's highest sulfate levels.

Environmental Research and Technology, Inc., of Concord, Massachusetts, is the prime contractor and will be responsible for the ground monitoring, as well as for the development of a mathematical model based on data collected from the study.

The airborne monitoring will be conducted by Meteorology Research, Inc., of Altadena, California, and Research Triangle Institute of Research Triangle Park, North Carolina.

Power Plant Waste for Agricultural Applications

Studying ways of using coal combustion by-products on a large agricultural scale is the objective of a new EPRI contract with Midwest Research Institute of Kansas City, Missouri. Researchers hope to find that waste materials can lend favorable properties to soil.

Harry Kornberg, manager of EPRI's Ecological Effects Program, said that fly ash (the residue formed from coal combustion that is caught by electrostatic precipitators) is used today on a limited basis to decrease acidity of soil.

Sludge (produced when gaseous effluent from coal burning is washed with lime) is being used on a small scale to increase porosity of soil. Sludge also can change the mechanical and chemical properties of soil to slightly increase its acidity, according to Kornberg.

All aspects of ash and sludge use in agriculture are being investigated by the contractor, including possible toxic effects. If it is found that the materials are beneficial on a large scale, the contractor will look into the economics of marketing them.

Kornberg stressed the need for the study because vast amounts of ash and sludge are produced each year and larger quantities will be produced in the future.

"Today, 600 million tons of coal are being burned a year, leaving some 60 million tons of ash," he said. "By the year 2000, we can anticipate that 1 billion tons (1 gigaton) or more of coal will be burned each year, which will mean that over 100 million tons of ash must be disposed of."

Kornberg also said that if from now until the year 2000 all coal combustion effluent is treated with lime, using current technology, "The sludge produced each year would be equivalent to a layer nine feet deep over an area the size of the city of San Francisco."

The EPRI program manager concluded that although there is no known hazard in storing the materials, it would be advantageous to find beneficial uses for them.

R&D Status Report
ELECTRICAL SYSTEMS DIVISION

John J. Dougherty, Director

DISTRIBUTION

Askarels (trade name for polychlorinated biphenyls [PCBs]) have long been used as the insulation/coolant in several types of electrical equipment, particularly in transformers installed in confined areas where potential fire hazard is of concern. However, since askarels are nonbiodegradable, they are no longer usable. A project with Westinghouse Electric Corp. is planned to develop an inert-gas–insulated and vapor-cooled transformer as a desirable substitute (RP930).

The objectives of the gas-vapor transformer project are to develop safe, oilless, fire- and explosion-resistant transformers at costs that are acceptable to the industry and that will eliminate environmental contamination. This project is sponsored jointly with the Substations Program. Three types and sizes of transformers are being developed. Each is expected to have dimensions, weights, losses, and other characteristics comparable to, or better than, oil-filled units. The vapors being tested are excellent insulators as well as coolants.

The principle of vapor cooling depends on the transfer of heat by a small quantity of vaporizing liquid. The liquid is applied continuously to the transformer windings and core by a recirculating system. On contacting the hot core and coil, the liquid vaporizes. The vapors carry heat to coolers, where the vapors condense, giving up their heat. The liquid then drains to the bottom of the tank, whence it is recirculated to the windings.

On energizing, the partial pressure of the vapor at ambient temperatures is normally too low to provide sufficient startup dielectric strength. A noncondensable gas (SF_6) is therefore used for the startup insulation medium. Tests on the first unit will evaluate a method of separating the SF_6 from the core and coil assembly and the radiators.

The three units to be built and tested during this research project are:

- A 15-kV, 2500-kVA gas-vapor secondary unit substation transformer, which is now under construction. It will have a voltage and power rating within the former askarel-insulated transformer rating range and is expected to replace a large number of those fire-resistant units. Construction and testing of the transformer is scheduled for completion by the end of 1977.
- A 34.5-kV, 1000-kVA network transformer that is fire- and explosion-resistant and will fit into existing network vaults. This unit will be completed by the end of 1978.
- A 34.5-kV, 5000-kVA transformer to cover the wider anticipated range of utility distribution needs. This unit will also be completed by the end of 1978.

Material and design work is progressing on all three units. Overall, the program will take advantage of existing background data as well as new development work.

A dielectric system was developed for the 15-kV unit through extensive material searches and dielectric testing. Some 230 chemical tests were used to screen the candidate materials for compatibility. Further thermal and dielectric screenings followed, including the testing of larger samples of materials in stainless steel aging tanks at higher temperatures.

Selected materials are now being tested in distribution-size, life-test models to further verify both the dielectric and thermal capabilities of all transformer materials in all configurations. The first life-test models exceeded the anticipated minimum test times at a hot spot level of 220°C, allowing construction to proceed on the first full-size unit. Other test temperatures on life-test models are under way.

The extensive model dielectric test program was expedited by a new research technique. A method was developed for obtaining impulse test data on models, which would eliminate the effect of charge buildup. Normally the charge buildup tends to yield higher breakdown values with successive tests, compared with the breakdown value of the first test. Because of the buildup, acceptable data had previously required disassembly and discharge of model materials before proceeding with the next higher impulse test level. The new technique provides comparable data without disassembly, greatly reducing testing time. The first test breakdown (using a 7-μs front impulse wave with a level approximately 150% of the expected breakdown level) correlated well with separate-discharge, multiple-test breakdown levels of transformer insulation.

Tests of fire resistance have also been made with preheated liquids under pressure. Excellent results were obtained with all the candidate liquids. Results to date indicate that the gas-vapor transformer will be a viable successor to the askarel over other indoor-type transformers. It will reduce the need for such safety measures as drainage pits, fireproof vaults, sprinkling, fire-extinguishing systems, and remote installations. The safer, gas-vapor transformer has the potential of filling the need now provided by several types of transformers, including oil-filled units. *Project Manager: Robert Tackaberry*

SUBSTATIONS

A thorough knowledge of switching-surge phenomena is becoming increasingly important to power system designers. Future ac line relays that are used to control fault current limiters and future high-speed (one-cycle) breakers will be operating in a range where they will be affected by switching surges. Moreover, new gapless arresters, which operate more frequently than their older counterparts, may be required. Their development will depend on an improved understanding of the duty cycle of the arresters.

Instrumentation systems

The main purpose of an ongoing project, an analysis of transients on transmission systems, is to gather data on the frequency and characteristics of switching surges (RP751). The data will be used to support design of digital relaying and substation equipment and to verify computer models used for transient analysis of transmission systems.

The contractor, Westinghouse Electric Corp., is in the process of designing and assembling two instrumentation systems that will be used to acquire the data. The instrumentation system will have a 100-kHz minimum bandwidth. The high-voltage measuring system consists of three high-frequency electronic current transducers and six coupling capacitors connected to electronic equipment for the voltage measurements. In addition, there are three instrumentation channels suitable for monitoring conventional current transformer (CT) secondary currents and three voltage channels suitable for monitoring the outputs from conventional potential transformers (PTs). Hence, the data acquisition system will be capable of recording data from 15 channels simultaneously.

The data acquisition system consists of a high-frequency digitizer with buffer storage and logic circuits for starting recording cycles. A tape memory is connected to the digitizer for storing the transient data. All the data acquisition equipment will be placed in a mobile trailer, which is being designed for unattended operation. The only duty of the operator will be to change tape reels when the recording tape has been filled with data.

The information that is directly recorded by the data acquisition system is not immediately useful to an analyst. Therefore, these raw data are first converted to a general data base, which is, in turn, processed on conventional, general-purpose computers.

The contractor has completed the general system design, as well as the detailed designs for many of the subsystems. Most of the equipment has been placed on order, and assembly of the instrumentation systems is in progress. The first instrumentation trailer was shipped during August 1977.

The two instrumentation systems will be installed in late 1977 in two substations owned and operated by the Florida Power & Light Co. It is expected that significant amounts of data can be collected within a short period of time with this system: As Florida has a high number of thunderstorm days per year, lightning-induced faults are frequent.

The instrumentation systems will continuously monitor two lines for at least a year. The data analysis will be made concurrently with data acquisition. A final report summarizing the project is expected to be published by late 1978 or early 1979. *Project Manager: Stig Nilsson*

Surge arresters

Power transformers and other high-voltage substation equipment can be made more reliable and less costly if overvoltage stresses can be reduced or eliminated. A considerable amount of effort has gone into development of today's surge arresters, which are capable of limiting surge voltages to approximately two per unit of normal line-to-ground crest voltage. Experts feel there is more to be gained in terms of reliability and cost by going down to one and a half per unit. Furthermore, it would be worthwhile to devise a surge arrester that is less susceptible to failure from shipping damage and leaks.

The development of metal oxide nonlinear resistors for use in surge arresters could be the best way to improve performance and reach the goals of improved reliability and lower cost. Besides surge arresters, it is conceivable that metal oxide nonlinear resistors will find application in fault current limiters, dc breakers, and series capacitor protection.

Metal oxide nonlinear resistors are usually made of zinc oxide, with small amounts of other metal oxides added as dopants. These oxides are blended together and pressed into appropriate cylindrical shapes, using processes well known to the ceramics industry. The blocks formed are fired in a kiln at high temperatures, which may be in the neighborhood of 1200°C. After firing, an insulating collar is applied to the cylindrical surface to prevent voltage flashover, and electrical contacts are applied to the two flat ends.

Over the past two years McGraw-Edison Co. has conducted many experiments to determine the effects and interactions among the numerous variables in this total process (RP425). They have identified the main effects of nearly a dozen potential dopants, developed mixing procedures to give uniformity to the materials involved, developed and optimized the firing schedule to promote uniform grain growth and optimum density, and developed automated testing procedures that greatly expedite the experimental process.

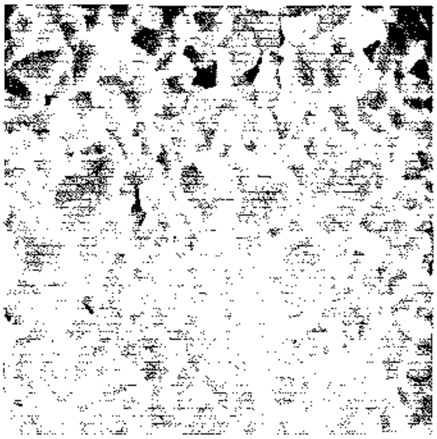
In addition, they have subcontracted a portion of the project to Marquette University, whose researchers are investigating the fundamental mechanisms involved in the functioning of metal oxide nonlinear resistors. They have developed a unified theory of operation that at least qualitatively explains all the phenomena observed and reported in the literature. Experiments will be continued to confirm and to quantify this theory. It is thought that with knowledge of the fundamental mechanisms, we will be better able to understand the effects of the chemical and processing variables.

The second task being undertaken at Marquette is an intensive study of the deterioration of metal oxide nonlinear resistors resulting from both surges and long-time energization at operating potentials. When completed, this work will contribute greatly to improved reliability.

So far, most of the experimentation at McGraw-Edison has been done with small laboratory-size samples. As information is gained, it will be necessary to scale up the process to sizes that can be used in commercial products. Concurrent with this work will be tests on the conduct of long-term stability. The project is scheduled to be completed in the fall of 1979, at which time we expect to have the knowledge necessary to design commercial metal oxide nonlinear resistors for many different applications. *Project Manager: Richard Kennon*

A contract on the development and use of metal oxide varistor blocks is also under way at Westinghouse Electric Corp. (RP657). Emphasis is on experimentation with the energy capability, the long-term stability, and the practical use of large-size blocks (up to 15-cm [6-in] diam) in arresters (Figure 1). Its primary objective is to develop compositions and processes to meet certain thermal energy and nonlinearity requirements of 500-kV and higher-voltage transmission system arresters. Its goal is a protective level of one and a half per unit maximum line-to-ground voltage for a surge current of 26 kA. In an effort to reach this goal, several formulations and processes have been developed, and voltage limiters rated 6-, 12-, and 30-kV have been tested that have superior protective characteristics, compared with existing gapped arresters. The varistor blocks developed under this project are also intended to be used in a prototype series capacitor protection scheme sponsored by the Bonneville Power Administration. *Project Manager: Narain Hingorani*

Figure 1 Cleaved surface of metal oxide varistor revealed by scanning electron microscope (SEM). The SEM is used to determine grain size, uniformity, structure, and porosity. It is also used in conjunction with an energy dispersive X-ray spectrometer to determine chemical composition and location of elements in the structure.



Voltage support

The need for voltage support and control of volt-ampere reactives (VARs) on transmission systems has long been recognized by utility planners and operators. Utilities desire a system that responds rapidly and accurately to the changing needs for both real and reactive power. These changes can occur slowly over a period of hours, or they can recur frequently during the day, as in the case of an electric arc furnace.

Another source of change on a utility system is the operation of the system's equipment, under both normal and adverse conditions. These include a wide variety of events, such as line switching, transmission outages, generating plant outages, and equipment failures.

In order to provide satisfactory service to customers, an electrical system must be able to restore itself to a stable operating condition following any of the changes described above. An important criterion of a reliable system is its ability to maintain adequate voltage at critical points.

The long-standing problem of voltage support has been the focus of much analytic work. Various types of reactive devices, such as inductive reactors, shunt capacitors, series capacitors, and others have been extensively studied and applied in numerous ways to improve the operation of utility systems. In addition, this application has resulted in other operating benefits, such as reduced losses, increased power transfer capability, and improved voltage regulation.

In recent years, there have been significant achievements in the field of solid-state power electronics. This technology may hold potential for the control of reactive power during various system operating conditions.

In 1977 EPRI arranged to have a static VAR generator (SVG) installed on a utility transmission system. This was an opportunity to test and evaluate its performance under a wide range of operating conditions. The EPRI project covers development, design, installation, and field testing of a 40-MVAR, thyristor-switched reactor, in parallel with two switched-shunt capacitor banks for control of the 230-kV line voltage on the Minnesota Power & Light (MP&L) Co. system (RP750). The thyristor switch assembly is shown in Figure 2.

The project has progressed to the point at which all system studies are finished, control strategies have been developed and modeled, hardware has been designed, and manufacture of all components is complete. Installation on the MP&L system is scheduled for this fall, and initial field tests should be complete before the first snow flies.

Fast response, low losses, low maintenance and low cost make the SVG a clear choice over rotating synchronous condensers for variable VAR supply on utility systems. A further advantage is that a static device will not contribute to fault current. *Project Manager: Richard Kennon*

OVERHEAD TRANSMISSION

Inductive coupling between gas pipelines and ac overhead transmission lines has long been a matter of concern to both the gas and electric industries. As a result of certain combinations, voltages can be induced in gas pipelines that may be too high, considering the equipment or the exposure. The practicing engineer needs easy-to-use techniques that accurately predict these voltages, as well as measures that reliably mitigate voltage effects on gas pipelines.

A project team, jointly funded by EPRI and the Pipeline Research Committee of the American Gas Association, has consolidated known data and made a systematic investigation into the mutual effects of ac electric power transmission lines and natural gas transmission pipelines that share rights-of-way (RP742). The results will be useful to both the electric power and natural gas transmission industries in answering questions arising from joint land use.

In order to fulfill the project objectives, the initial task was to search the literature for pertinent information. Such information has now been collected, assessed, and summarized, and where gaps in knowledge were recognized, research was conducted to advance the level of knowledge. To date, the significant project accomplishments include:

- Unification and generation of new coupling prediction methods
- Development of simple programs for use with hand-held calculators

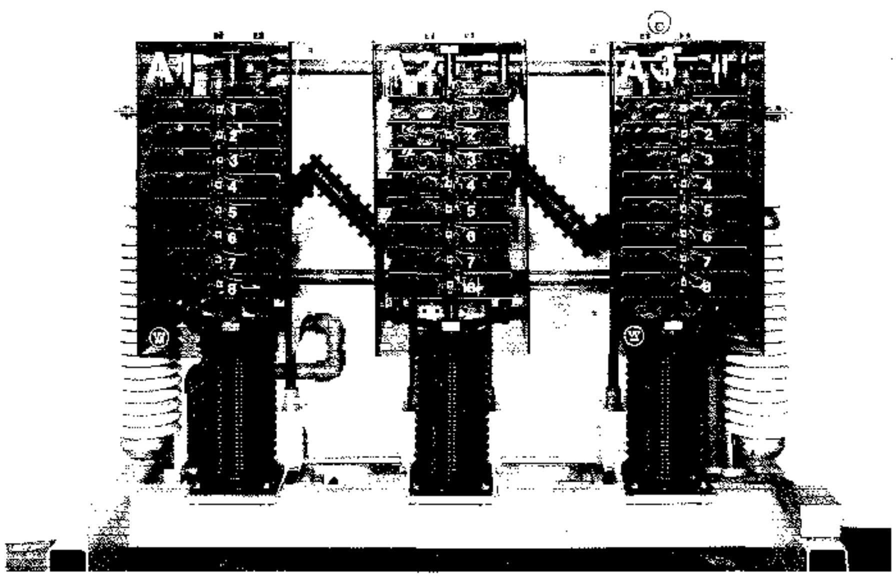


Figure 2 Thyristor switch assembly that will control current through 13.8-kV shunt reactors of the static VAR generator to be installed on the Minnesota Power & Light Co. system.

▫ Evaluation of available mitigation techniques and the proposal of new measures

▫ Estimation of ac corrosion levels and summary of pipeline component reliability data

Field tests have been conducted on a long run of joint gas and electric right-of-way in the southern California desert. Steady-state coupling theories have been confirmed, and one proposed mitigation technique has been proven technically valid. *Project Manager: Richard Kennon*

SYSTEM PLANNING

The real and reactive power drawn from the utility substation buses, usually referred to as the load, changes rapidly as the system voltage or frequency varies. This variation is usually the result of a major disturbance, such as the loss of a generating plant or the opening of a major tie line. It has been demonstrated in many studies that a rapidly changing load can diminish power system performance and security.

At present, we cannot accurately predict how changes in voltage or frequency will affect the load level.

A project is under way that will develop procedures to accurately predict what changes in the load demand are actually caused by a change in the system voltage and/or frequency (RP849). The project contractors are: General Electric Co., University of Texas at Arlington (UTA), Hydro-Quebec Institute of Research (IREQ), Dr. Gerald Park of Michigan State University, and Dr. Fred Schweppe of Massachusetts Institute of Technology (MIT).

Two parallel approaches are being pursued. The component approach, which is under investigation by UTA, arrives at load behavior solely on the basis of an understanding of the behavior of individual load components. The testing approach, which is used by General Electric, obtains load behavior information from on-line tests. IREQ is responsible for the design of a digital data acquisition system that will be used in the field tests.

In the component approach, UTA first compiled a list of such major load components as fluorescent lights, air conditioners, heaters, and so on, and performed laboratory tests on each. An assortment of these components, representing utility summer or winter load composition types, were then assembled at the Trinidad test facility of Texas Power and Light Co. An artificial distribution feeder was inserted in series with the aggregate load to provide a scale model of a utility distribution feeder, including connected loads. Tests were performed on the scale model feeder to determine the response of the aggregate load to voltage and frequency change.

UTA will use these test results to construct an analytic load model. An industrial guidance board consisting of utility engineers from over 20 companies has been set up by UTA to provide feedback and guidance on the progress of the project, which is scheduled for completion in mid-1978.

In the testing approach, General Electric, with support from the New York Power Pool (NYPP), will conduct tests on the substation loads of two NYPP member companies: Long Island Lighting Co. and Rochester Gas and Electric Co. Voltage changes will be obtained via transformer tap changers and VAR control devices. To perform frequency tests, the substation to be tested will be switched from the normal system supply to an isolated source supplied by a combustion turbine. The governor control of the combustion turbine will be regulated to achieve the desired frequency changes.

Test data will be recorded by the Real Time Digital Data Acquisition System (RTDDAS) constructed by IREQ. The RTDDAS will be housed in a 9.1-m (30-ft) trailer and will be equipped with 16 recording channels. It will be capable of a maximum speed of 30,000 samples per second at accuracies of 0.025%. Switching surge protection will be installed in the RTDDAS so that it can operate in any high-voltage substation. At the end of this research project the RTDDAS will be available for loan to other utilities that want to perform similar tests on their systems.

The first load test will be conducted in May 1978. Two backup tests are scheduled for the winter of 1978 and the summer of 1979.

After these tests, a special system identification data processing package will be used to process the voluminous test data. The test data will be analyzed and compared with the analytic results developed by UTA.

At the end of the research project, which is scheduled for completion in December 1979, utility system planners will be provided with these results:

▫ An analytic procedure to construct a load behavior model. The model will require load composition information as input.

▫ A testing package to validate and supplement the load model developed by the previous step. The testing package will include suggested test procedures, the RTDDAS, and the computer software for processing the test data.

▫ A procedure to implement the load model, obtained from either of the previous two steps. This can be done by conventional transient stability computer programs, load flow programs, or by the EPRI Long-Term Power System Dynamics (LOTDYS) computer program.

It is expected that the model of load behavior provided by this research will enable power system engineers to significantly improve the accuracy of system studies. This, in turn, should result in more efficient use of the generation and transmission facilities and greater power system reliability. *Project Manager: Tim Yau*

UNDERGROUND TRANSMISSION

Growth in the use of extruded dielectric cables in transmission systems is slow, despite their favorable economics. This is partly due to concerns over their reliability. Since new installations are being made at a rate of approximately 10,000 mi/yr in the distribution area, the availability of more reliable cables would allow substantial savings to be realized in addition to reducing maintenance.

The reliability of extruded dielectric cables depends to a large extent on the cleanliness of the insulation and its freedom from impurities. Contaminants are responsible in part for electrochemical treeing, a long-term deterioration process. They can also give rise to electrical treeing, a short-term deterioration process.

In a new project, Reynolds Metal Co., in conjunction with Food Technology Corp. of Rockville, Maryland, will develop a system capable of inspecting and rejecting individual, contaminated polyethylene pellets prior to their entry into cable insulation extruders (RP7865). The approach will be based on an optical detection system and a pellet ejection system, the principle of which is now being employed by Food Technology Corp. in food processing. A high-speed, high-resolution optical system will "look" at a moving stream of polyethylene pellets and detect individual contaminated pellets through small changes in light reflection caused by the darker contaminants. Having determined the position of the contaminated pellet, the system will eject the pellet from the processing stream.

The project will examine the applicability of this system in the cable industry, in particular, its ability to operate economically at normal production speed. *Project Manager: Bruce Bernstein*

Refrigeration equipment

Refrigeration and auxiliary equipment used to force-cool underground high-pressure oil-filled (HPOF) power cables are expensive portions of an underground transmission system because they require large plots of land. Since land is extremely expensive in urban areas, and conventional refrigerators cost approximately $1000/t of cooling, EPRI's Underground Transmission Program is initiating development projects that are aimed at reducing capital cost, land requirements, and maintenance costs of refrigeration equipment.

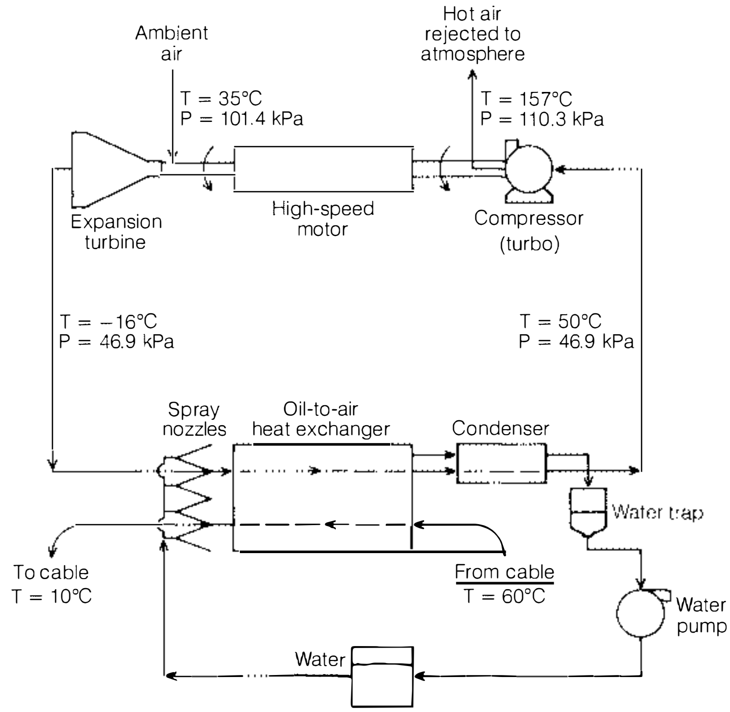
A project that has just been initiated with AiResearch Division of Garrett Corp. will develop air-cycle turbomachinery, based on a subatmospheric Brayton refrigeration cycle, for steady-state (continuous) cooling and/or auxiliary emergency cooling of high capacity oil-filled cable (RP7866). These cooling units are very small, can be fabricated by using a modular approach for tight areas like manholes, and are inexpensive compared with conventional refrigerators. It is anticipated that once manufactured in quantity, these units could cost approximately one-third that of Freon cycle units. Moreover, the units could provide savings in land requirements.

The basic components of an air-cycle cooling unit include a high-frequency driving motor, an expansion turbine, an air compressor, and some sort of heat exchanger (Figure 3). By adding a water evaporation and recovery system that injects a spray of water over the heat exchanger, a nominal 16-t (56.3-kW) unit can have its cooling capacity increased to 45 t (158.3 kW). This uprating is accomplished by using the latent heat of water vaporization. No changes in the basic equipment need be made.

The air-cycle unit being developed uses an open refrigeration cycle, as is evident in the temperature versus entropy curve (Figure 4). For this unit the use of the open cycle is one of convenience, since air is being used as a refrigerant. A closed cycle can be used when other refrigerants are considered and lower coolant temperatures are required (Figure 5).

The unit's versatility could make air-cycle cooling attractive not only for emergency cooling but also for use as a permanent refrigeration station. *Project Manager: Thomas Rodenbaugh*

Figure 3 Block diagram of an air-cycle heat exchanger that shows the high-frequency driving motor, expansion turbine, air compressor, and oil-to-air heat exchanger. This unit can be fabricated in modular form to fit in a manhole at low cost.



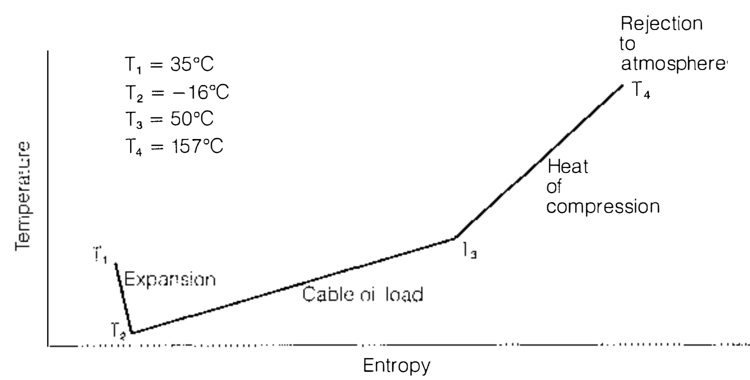
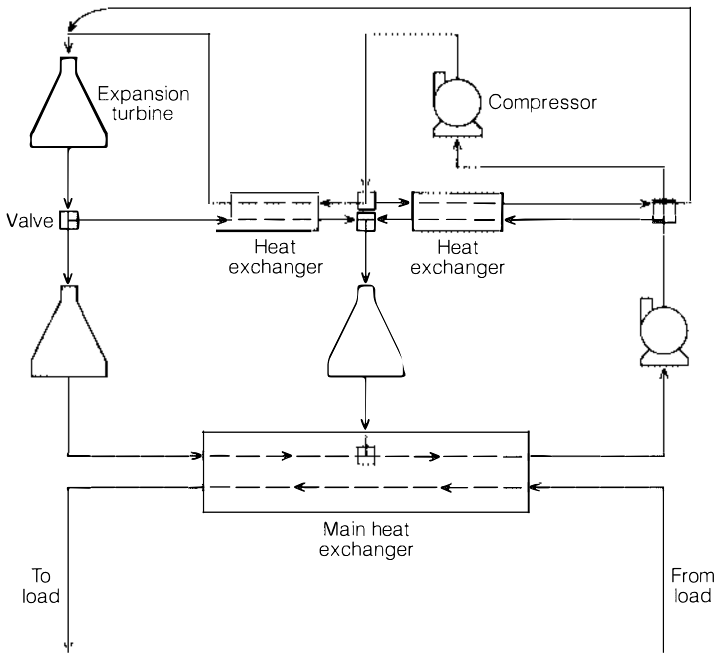


Figure 4 Entropy curve of an open-cycle refrigeration unit shows its ability to intake air at a relatively high ambient temperature (35°C; 97°F) and to expand the air to a very low refrigeration temperature for maximum cooling effect.

Figure 5 Configuration of a closed-cycle refrigeration unit, which offers lower coolant temperatures with little increase in cost.



R&D Status Report
NUCLEAR POWER DIVISION

Milton Levenson, Director

COPPER ATTACKS GOLD IN HIGH–TEMPERATURE WATER

The unexpected phenomenon that a small amount of copper dissolved in water at 300°C can oxidize gold has been observed in an EPRI-sponsored experiment.

EPRI is trying to determine the properties of high-temperature water in contact with the metals commonly used in reactor piping, steam generators, and turbine internals. The operating temperature of LWRs is in the range of 290°C to 350°C. Most water chemistry and corrosion measurements have been performed at temperatures more accessible to laboratory study (i.e., less than 100°C). Subtle but significant changes between room temperature and 300°C have been observed.

Recently, the research contractor dealing with the thermodynamics of the dissolved ions of metals of the common alloys used in LWRs has discovered a new property of the cupric ion—dissolved copper with an oxidation state of plus 2, Cu^{++}. In brief, the cupric ion at 300°C and at low concentration has been observed to oxidize gold. Gold was present in the autoclave on the assumption that it would not be attacked by any of the constituents being studied. Copper in the plus-2 oxidation state is apparently an exception.

The significance of this finding has yet to be determined. It is a signal, however, that copper in dissolved form at 300°C may be far more altered in its behavior than most of the ions under study thus far and therefore may be an especially significant impurity in LWR water systems. This discovery was made at San Diego State University under the direction of Dr. James W. Cobble (RP311-2). His principal assistant, Dr. Richard C. Murray, observed gold particles in the high-pressure autoclave calorimeter following each 300°C run with cupric chloride.

The experiment was repeated, with the same result. Investigation led to the discovery that the gold weight used to break the quartz ampul to release the salt at high temperatures was being attacked by the solution. Subsequent cooling to room temperature apparently caused the gold to reprecipitate as gold metal particles from its as-yet-unknown condition in solution at high temperature.

The project at San Diego State was not designed to study unusual and unexpected reactions at high temperature but rather to measure the fundamental properties of the metal ions at 300°C, free of disturbing side effects. The calorimeters are made of such materials as titanium, noted for chemical inertness. Gold is used as a high-temperature gasket on the head of the autoclave, as well as for the weight that is magnetically released to break the sealed quartz ampul containing the salt until the desired temperature is reached.

It is surprising to find these reactions under conditions designed to avoid them. Work will be performed with a titanium-encased gold weight to prevent such reactions interfering with future thermodynamic measurements. But, the aggressive behavior of copper in this instance warrants further investigation. For example, the cupric ion may similarly attack other metals of far greater importance to LWRs than gold. Further significance may be attached because the presence of copper in steam generators appears to have a role in the serious corrosion process known as denting.

Probably the most significant feature of this discovery is reinforcement of the philosophy on which this study was based: the chemistry in 300°C water cannot be fully predicted from work done at room temperature without experimental measurements tying down the key parameters. Because of the difficulty of doing detailed experiments at such high temperatures as these, it is hoped that not all elements will behave in a grossly altered pattern from their room-temperature behavior. The copper result will make us somewhat more skeptical of data that are extrapolated from lower temperature measurements and are not based on direct experimental evidence at the high temperatures.

By the end of the current contract year, 300°C measurements will have been completed for both copper and cobalt, with some data on iron at the highest temperature. A complete report on this three-year project will be issued in early 1978. Two annual reports have been published and are available. These contain the basic data on oxygen, hydrogen peroxide, and hydrogen in water up to 300°C; data on the dissociation of the commonly used basic amines (used in pH control of secondary systems); and the 300°C extrapolated thermodynamic functions for the important nitrogen-containing aqueous species. *Project Manager: Thomas O. Passell*

COMPUTER–AIDED EVALUATION OF OPERATOR PERFORMANCE

In May 1976, EPRI initiated research on a performance measurement system for training simulators—one capable of automatic recording of statistical information on operator action and plant response. The objective was to design, install, and test run a system and plant response on the Browns Ferry nuclear power plant training simulator (RP769, General Physics Corp.).

The following exercises were developed in the initial 15 months: reactor criticality, plant startup, scram from high power, and main steam isolation valve closure. Key variables and actions suitable for monitoring by the training simulator computer were identified and programmed. For operator actions that the computer could not monitor, checklists were prepared in a format that minimized the subjectivity of the instructor's evaluation.

The performance measurement system is expected to become a useful tool for future EPRI research projects. However, the cost of training simulator time is high; to keep research program costs reasonable, the measurement system is being designed as an integral part of operator training programs. Enthusiastic cooperation in the development and improvement of the measurement system can be expected from training staffs if they perceive the system as useful in the training programs.

Origins of project

Three studies played important roles in starting the project. The first was the *Reactor Safety Study,* WASH-1400, which in one section performed a human reliability analysis to estimate the influence of human errors on the unavailability of various safety systems and components (*1*). The principal author of that section, Alan D. Swain, made the following complaint: "An actuarial data base for human error rates in nuclear power plants does not exist. Although AEC does collect information on human errors associated with abnormal power plant incidents, the data are not generally in a form usable for human reliability analysis."

It was Dr. Swain's view that a well-designed simulator-based performance measurement system could help provide a satisfactory data base.

The second study was performed under an EPRI project on human factors review of nuclear power plant control room design (RP501, Lockheed Missiles & Space Co., Inc.). In that study (*2*), the human factors of five representative nuclear power plant control rooms were evaluated, using such methods as 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. Many improvements in current practices were suggested.

The third study was performed by the Simulation Products Division of the Singer Co. (*3*). In that feasibility study (TPS 75-26), Singer performed the following tasks:

- Surveyed automated simulator performance practices, past and present, in the U.S. and foreign electric utility industries, in the aerospace industry, and in the U.S. military
- Identified options of which parameters are to be recorded and in what format records are to be stored
- Investigated the types of simulator hardware and software modifications that are necessary to implement the performance measurement system
- Developed an estimate of the cost and simulator downtime that would be required to install a performance measurement system

The present project is a direct follow-on to that feasibility study.

Description of measurement system

With need and feasibility established in the above studies, EPRI contracted to implement the performance measurement system for four drills on the Browns Ferry training simulator. The objectives of the project were to:

- Provide an empirical data base for statistical analysis of operator reliability and for allocation of safety and control functions between operators and automated controls
- Develop a method for evaluation of the effectiveness of control room designs and operating procedures
- Develop a system for scoring aspects of operator performance to assist in training evaluations and to support operator selection research

The function of the performance-measuring system is to collect and evaluate simulator data. During a simulator exercise, all control room data (gages, annunciator lights, switch and knob positions) are collected on magnetic tape. The taped data are evaluated by a computer after the exercise has been completed. The evaluation programs can be written in FORTRAN and changed according to the needs of the users.

The operation of the system is shown in Figure 1. The simulation programs have four types of inputs and outputs.

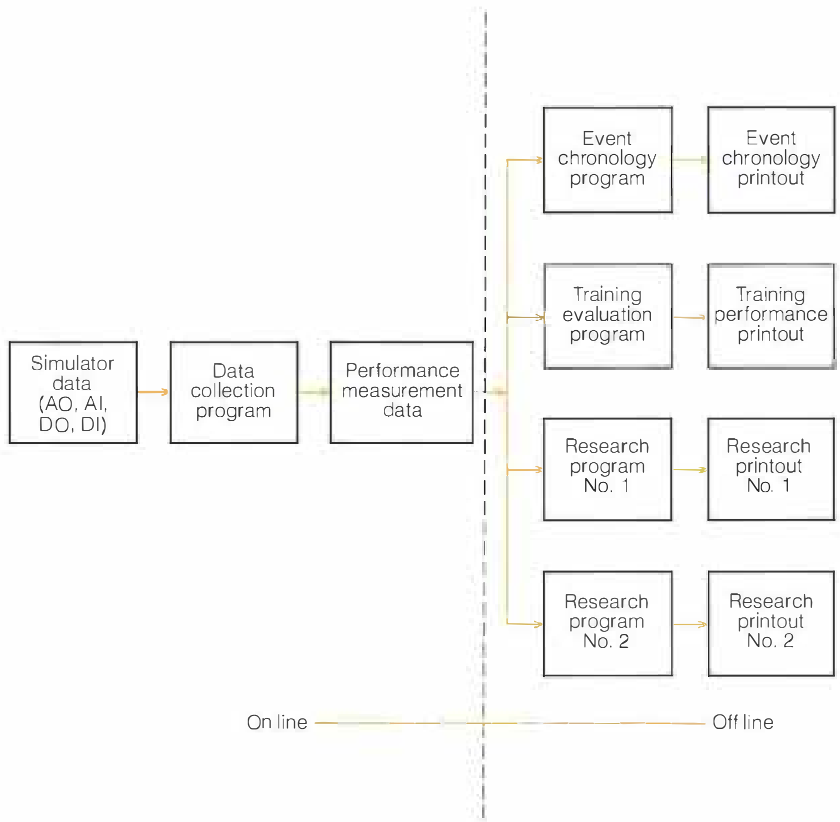


Figure 1 The structure and operation of the performance measurement system. Four types of data input and output are received by the data collection program and stored on magnetic tape. The data can then be compiled in a number of ways by different computer programs and printed out.

Digital inputs (DI)—discrete inputs from the control room to the simulation programs. An example is the position of a two-position switch on one of the control panels.

Digital outputs (DO)—discrete outputs from the simulation programs to the control room. An example is the signal to an annunciator light, turning it on or off.

Analog inputs (AI)—continuous inputs from the control room to the simulation programs. An example is the position of a control knob on one of the control panels.

Analog outputs (AO)—continuous outputs from the simulation programs to the control room. An example is a meter-reading on one of the control panels.

Simulator data, the AOs, AIs, DOs, and DIs, are collected by a data collection program and stored on magnetic tape. This is concurrent with the normal operation of the simulator (i.e., on line). The data collection program is added to the basic simulation program. This program must be written in assembly language for the Browns Ferry simulator, as that language is used in all the simulation programs on the simulator.

At the end of an exercise, there is a complete and permanent record of all the simulator data presented during the exercise. These data can then be used to compile any of a number of different types of printouts by using different computer programs, which are implemented off line (i.e., when the simulator computer is not being used to drive the simulator). Evaluation of the data can also be done on a computer other than the one at the simulator.

The researchers debriefed each of the subjects. At the conclusion of the structured-interview portion of the debriefing, the test subjects were asked to give their opinions on the foreseeable advantages and disadvantages of the performance measurement system. This questioning revealed a highly favorable attitude toward the purposes of the measurement program. The major advantages highlighted were:

- The program gives the trainer another evaluation tool, one that is more objective than the instructor. This tool cannot be relied on too heavily, however, as some subjective observations made by the instructor (which cannot be measured by a computer) are important.

- An instructor may be hesitant to tell utility management that a trainee's performance is unsatisfactory. The measurement system offers a standard by which to make such a decision. If, for example, a trainee consistently makes 16 errors per exercise and the norm is only 1 or 2, then the instructor can use the hard copy of the exercise results to justify his evaluation.

- Instructors may be influenced by their personal likes and dislikes. There is a tendency to give the "nice guy" a break. Other trainees may be downgraded unfairly. An instructor may also tend to equate good performance with an operating style most like his own (e.g., "He operates the board as I think I would."). An objective measurement system counteracts these factors.

- Instructors can disagree over the effectiveness of a trainee. The computer could help settle such differences.

- The measurement system could pinpoint errors or deficiencies that the operator is not aware of. He can avoid these problems in the real plant.

- The measurement program may help discern whether an operator has supervisory capacity, can make decisions, and has self-confidence.

- The program may lead to layout changes on the boards, perhaps achieving more compact control boards.

The potential pitfalls associated with the program mentioned by the interviewees were:

- The way the scores are treated can create problems. Is NRC going to look at the scores? If the scores are in the files, NRC may demand to see them. An operator's license, as well as his professional reputation, may be jeopardized.

- The measurement system may be too restrictive. The computer records that an operator went to a 27-in vessel level instead of a 28-in level (error limit). This may not be a problem—some people get excited when a set point is reached, while others are more permissive. It depends on the situation: It's one thing if the operator is overloaded and vessel level gets to 27 in. If the operator is not overloaded and it gets to 27 in, then a problem exists.

- Operators vary from day to day and the exercise may not be a good evaluation. Data should be collected more than once for each operator on each exercise.

Research studies

After the performance measurement system has been implemented on a routine basis, several research efforts can use the data collected. Training research can measure performance changes due both to training and to the time between refresher training periods. Operator selection researchers can use the performance measures to supplement other performance criteria, such as supervisors' ratings, and can correlate the resultant ratings with scores on selection tests. Control system and control room design researchers can use the measures to evaluate design options in a realistic but controlled environment.

The performance measurement system shows promise for routine assistance to the staffs at nuclear power plant training simulators. Further, it has demonstrated the ability to gather data for a variety of research purposes. A planned follow-on project should provide ample opportunity for data collection and analysis, and a three-year extension has been authorized. *Project Manager: Randall W. Pack*

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2. *Human Factors Review of Nuclear Power Plant Control Room Design.* Report for RP501, prepared by Lockheed Missiles and Space Co., Inc., November 1976. EPRI NP-309-SY (Summary Report); EPRI NP-309 (Final Report).
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FORT ST. VRAIN DOCUMENTATION

The Fort St. Vrain Nuclear Generating Station, embodying the second U.S. (first commercial-scale) high-temperature gas-cooled reactor (HTGR), is located approximately 35 miles north of Denver, Colorado. Public Service Co. of Colorado (PSC) is the owner/operator of the 330-MW (electric) demonstration station and General Atomic Co. (GA) is the prime contractor with responsibility for design and construction of the facility.

EPRI has contracted with S. M. Stoller Corp. to provide extensive documentation of experience gained during the construction and startup of the plant. The purpose of the project is to identify problems encountered and their resolution in order to provide utilities with a useful record of the experience. In many cases, the information is applicable only to the HTGR concept. However, a good deal of the experience could be generally applied in any project attempting to design and construct an advanced facility as a demonstration unit. Through the cooperation of PSC and GA, the contractor has compiled an extensive record of the technical difficulties encountered at the Fort St. Vrain plant. Such information is often lost in the desire to get a plant operating, which results in unnecessary repetition of costly mistakes in the design and construction of later plants.

Description of plant

The reactor core consists of an array of hexagonal graphite blocks approximately 6 m (20 ft) in diameter and 4.6 m (15 ft) high. The fuel is contained in coated microspheres suspended in cylinders of graphite matrix material, which are placed in holes drilled in the graphite blocks. The core is cooled by high-pressure helium flowing downward through flow holes in the graphite blocks.

Helium in the primary circuit is driven by helium circulators powered by cold reheat steam under normal power operating conditions. A Pelton wheel drive is attached to the steam drive to provide a secondary means of power for circulation at lower flow rates when steam is not available. The circulating helium flows through steam generator modules containing reheat steam and main steam bundles to produce 538°C (1000°F) steam under design conditions.

Documentation

The report will be divided into three sections covering construction and preoperational testing, core loading and low-power physics testing, and rise-to-power testing. Each of these sections will be subdivided into a number of subsections covering various portions of the plant and will provide the following information:

- System description
- Test objectives and description
- Problems encountered, together with resolution of each problem (including a description of system redesign, if necessary)
- Significance to future HTGRs (the applicability to and implications for large HTGR design)

The construction and startup of a new plant design affords an excellent opportunity to obtain a great deal of important information on the performance of actual systems. Such data are often lost in the rush to get the plant operating. Further, there can be an understandable reluctance on the part of the designers and operators to release detailed information about problems encountered. Fortunately PSC and GA have recognized the importance of such information to future plants and have cooperated fully. The personnel at the Boulder, Colorado, office of S. M. Stoller Corp. have extensive HTGR experience gained through previous employment with GA and at the Fort St. Vrain plant, allowing an in-depth and objective coverage of the plant activities.

Coverage of general startup activities terminated at the end of June 1977, with the plant at the 30% power level in the rise to full power. A report on the documentation generated by the project through that date will be available shortly. The project will continue on a more limited basis through the first part of 1978. *Project Manager: J. Kendall*

R&D Status Report
ENERGY ANALYSIS AND ENVIRONMENT DIVISION

René Malès, Director

ECOLOGICAL EFFECTS OF THERMAL POWER PLANT COOLING SYSTEMS

The Environmental Assessment Department is supporting 11 research projects and 1 technical planning study on ecological assessment of the impact of thermal power plant cooling systems on aquatic environments (Table 1). Recently, the department has sponsored three conferences on the subject, including the Third National Workshop on Entrainment and Impingement (New York City, January 1976) and the Conference on Assessing the Effects of Power Plant Induced Mortality on Fish Populations (Gatlinburg, Tennessee, May 1977). The former was cosponsored with the New York Power Pool, the latter with ERDA. The objective is to develop the necessary methodologies and information to assess cooling system ecological effects and to assist the electric power industry plan generating capacity.

In September 1975, EPRI held an advisory workshop at Asilomar, California, attended by representatives of the electric power industry, academic and research institutions, and government, to discuss needed research in the area of cooling systems effects. The workshop generated many ideas that have been incorporated into about a half-dozen requests for proposals, from which the core of the research developed.

Research projects have been integrated around central themes: analysis of effects on the population and ecosystem level, ecosystem management, and chemical effects. In addition, several information base projects that could be classified as support studies have been developed.

An information meeting in mid-June was attended by all the contractors and a small advisory group of eminent aquatic scientists with a broad range of backgrounds. The objectives of the meeting were to derive an overview of how the effort was developing and to provide a forum for the contractors to meet one another and see how their projects integrated (a major feature of the program is the integration of individual projects). The information meeting resulted in stimulating, fruitful interactions among the contractors and helpful suggestions from the advisory group. Such meetings will probably be held annually.

Some of the projects are now sufficiently advanced for results to be reported. From industry sources, the Atomic Industrial Forum (AIF) has identified and compiled information and data relevant to assessing thermal power plant cooling system impacts on aquatic environments (RP877-1). These documents are commonly referred to as part of the "gray" literature because they are internally published, have limited distribution, and are not easily accessible to parties outside the organization publishing them. However, the documents contain in-

Table 1
ECOLOGICAL EFFECTS OF THERMAL POWER PLANT COOLING SYSTEMS

EPRI Project No.	*Objective*
RP573	Perform an ecological and economic assessment of a cooling lake fishery and develop a mathematical model for management of the fishery. A major feature of the assessment will be an ecological comparison of the cooling lake with a similar lake not used for cooling.
RP853	Develop a preliminary computer-oriented classification scheme of power plant cooling systems and cooling bodies of water to aid in the design of ecological effects assessment studies and in the extrapolation of research results from one site to another.
RP876	Develop and test a methodology for assessing population and ecosystem effects related to the intake of cooling waters.
RP877-1 RP877-2	Prepare a computer-searchable annotated bibliography of literature and data relevant to the assessment of the effects of thermal power plant cooling systems on aquatic environments.
RP878	Develop and test a methodology to assess integrated effects of multiple power plants on a single body of water.
RP879	Evaluate performance of available techniques and instruments for determination of oxidative residuals produced as a result of chlorination of power plant cooling water.
RP880	Perform a critical synthesis and analysis of existing ecological data for cooling impoundments with load ratios (impoundment surface area in acres/plant capacity in MW [electric]) less than 10.
RP881	Develop and test a methodology to evaluate the net social impact of cooling impoundments.
RP1063	Determine if different populations of the same fish species have different thermal tolerances.
RP1111	Develop potential of Leslie matrix technique to analyze impact of power-plant–induced mortality on the dynamics of fish populations.
TPS77-701	Assess environmental effects of selected alternatives to intermittent chlorination for biofouling control in cooling systems.

formation of value to the entire industry. Collectively, the documents can be used as a basis for critical reviews to derive generic results regarding cooling system effects. They can also be used as reference material to guide new studies being undertaken by the industry. It is more efficient and less costly for EPRI to support a project to identify and create an annotated bibliography of this information than for each electric power company to do the same. In addition to producing an annotated bibliography, AIF has created a central depository for the original documents.

As of June, AIF had obtained 1200 documents related to 316a and 316b studies (aquatic ecosystem studies required in connection with the enforcement of the 1972 Amendments to the Federal Water Pollution Control Act, PL92-500) and other electric power industry cooling system impact studies; 25 sets of nuclear environmental reports and impact statements (all such reports published); and 120 sets of fossil fuel environmental reports and environmental impact statements. Documents related to industry studies were identified by a questionnaire that was sent to 220 companies. Responses numbered 208, of which 124 indicated involvement in research/monitoring programs on cooling system impacts. These companies identified approximately 1000 documents reporting on the results of these programs. (The subject areas of primary concern are shown in Table 2.)

Complementing the work of AIF, Oak Ridge National Laboratory (ORNL) is compiling an annotated bibliography and creating a central depository for information and data found in "open" and in government literature (RP877-2). Open literature comprises books, theses, and articles in professional journals. Government literature consists of documents published by state and federal agencies and their contractors.

Both the ORNL and the AIF bibliographies are available for searching on a cost-reimbursable basis. In addition, their depositories are available for use. Within the next few months the two bibliographies will be merged and a user's manual prepared and published. Also to be published are three selective subsets of the merged bibliography, which will cover chemical effects, impingement, and entrainment. A review of the literature on thermal effects, based on the bibliography, was published recently by Coutant and Talmage (*Journal of the Water Pollution Control Federation,* Vol. 49, pp. 1369–1425, June 1977). EPRI plans to support AIF and ORNL in updating and maintaining the merged information base. AIF will provide searching services for the merged base. It is also planned to expand the base to include all cooling system environmental effects, not only effects on aquatic ecosystems.

Table 2
SURVEY OF UTILITY MONITORING OF COOLING SYSTEM IMPACTS
(figures based on 154 respondents)

No. of Responses	*Areas of Primary Concern*
98	Thermal effects on receiving body of water
78	Intake impingement and entrapment of biota
72	Thermal effects on aquatic biota
67	Entrainment of aquatic biota
41	Chemical effects on receiving body of water
36	Intake system design
35	Chemical effects on aquatic biota
28	Discharge system design
12	Other*
48	No response

*Other responses included: Use of sewage effluent, supersaturation of fish, EPA requirements, woodborers in marine wood, hydrothermal modeling, population dynamics, population estimations by markrecapture, radiological effects on aquatic biota, discharge effluent, operation parameters, hydraulic effects, and aquaculture.

All the projects listed in Table 1, except the evaluation of the cooling lake fishery (RP573), have been started within the last year. RP573 is in its third and final year. The cooling lake being studied is Lake Sangchris in central Illinois. Voluminous amounts of data have been collected on its phytoplankton, zooplankton, and fish communities, as well as on those of Lake Shelbyville, the noncooling lake with which Sangchris is being compared. Preliminary analysis of the data indicates that although there are some differences in species presence and abundance at all trophic levels, and some differences in spatial and seasonal species and community dynamics, the structure and functioning of the Sangchris ecosystem is not radically different from Shelbyville. Sangchris supports an excellent largemouth bass sport fishery, and there is no evidence that the power plant is having any major detrimental impact on it. In fact, there is evidence that the power plant may be an active factor in improving the fishery.

Some specific preliminary results are: Total fish catch per unit effort in Lake Sangchris (59.2 kg—132 lb) is lower than that in Lake Shelbyville (88.0 kg—194 lb), but the more diverse fauna and the greater abundance of nonsport fish species (gizzard shad and carp) in Lake Shelbyville account for most of the difference. The more diverse fauna in Lake Shelbyville is due primarily to a more diverse initial stock when the impoundment was built, a more diverse habitat at Lake Shelbyville, and the larger tributaries that feed into the lake. The biomass of sport fish in Lakes Sangchris and Shelbyville is relatively high (approximately 25% of total catch), compared with the standing crop of predatory game fish in reservoirs of the mid-South (15% of the total catch). Lake Sangchris has not experienced the decline in production of largemouth bass with impoundment age that is commonly observed in Illinois noncooling reservoirs. Reproduction of channel catfish is relatively more successful in Lake Sangchris than in Lake Shelbyville. Fish production in Lake Sangchris is intermediate—between the standing crops of fish found in reservoirs in the mid-South and the Midwest. On average, largemouth bass grow more rapidly in Lake Sangchris than in Lake Shelbyville and other noncooling lakes at similar latitudes. The extended growing season due to the thermal discharge is primarily responsible for the enhanced growth of largemouth bass in Lake Sangchris.

Data from RP573 have been used by Commonwealth Edison Co., Illinois Power Co., and Central Public Service Co. in 316a demonstrations. A number of consulting firms have used the data in power plant siting and design studies, and a number of research groups have used the data to support their own research. Along these lines, analytic methods and information resulting from RP876 have been used in a 316b demonstration by Hudson River utilities.

In the near future, EPRI's Environmental Assessment Department plans to develop projects around a new theme—biological engineering solution for reducing entrainment and impingement mortality. This research will be planned and supported jointly with the Water Quality Control and Heat Rejection Program in the Fossil Fuel and Advanced Systems Division. New intake concepts, such as the porous dam, for filtering fish and shellfish eggs and larvae will be examined. Research designed to quantify the contributions of different factors to entrainment mortality will be considered. *Project Managers: Robert Goldstein and Robert Kawaratani*

COAL AND URANIUM PRICE FORMATION

Coal and uranium price formation is the result of complex interactions between resource owners, miners, transporters, consumers, governments, and others in the marketplace. As part of an effort to develop supply schedules (price-quantity relationships) for coal and uranium, EPRI contracted Charles River Associates, Inc. (CRA) to prepare a documented analysis of the economic process of price formation in the coal and uranium industries over the past few decades (RP666). The results of their analysis will be published this fall (*Coal Price Formation* EPRI EA-497; *Uranium Price Formation* EPRI EA-498). Following are CRA's conclusions.

Coal

Long-run equilibrium prices are based on the average cost of new mines. The force of competition and the conventions in large coal transactions lead to minemouth prices that are based on extraction costs with some small percentage for royalties. The new mines, which determine prices, are large underground operations in the East and Midwest and large strip mines in the West.

There is no simple fuels price parity mechanism forcing coal prices into line with other fuels. Though coal prices correlated with oil prices through 1974, the long-run trends in these two prices may well diverge. Oil prices are determined by a mix of complex forces, perhaps including to some extent the price of coal in the U.S., but coal prices can move independently of essentially exogenously determined oil prices. Competition among coal suppliers is a more powerful mechanism for coal price determination than the competition between coal and other fuels.

Short-run price determination is related to excess capacity-of-factor inputs. Short-run price determination has varied in different historical periods. Before 1969 there was sufficient coal mining capacity, especially from smaller mines, and a reserve pool of labor that was adequate to allow rapid output increases in response to modest unanticipated coal demand increases. After 1969 the reservoir of experienced labor, especially for deep mining, decreased and the ability of small mines to increase output or come on stream was limited by new government regulations and reserve depletion. Consequently, price swings in response to demand increases have become more dramatic in the short run than they were before 1969.

Labor supply adjusts relatively slowly. In both coal industry decline and growth, the supply of labor historically has lagged in response to output and productivity changes, especially in underground mining. Labor force formation and migration are by nature slow processes. Unlike many other industrial sectors, coal production is bound to well-specified regions and cannot move to areas where labor conditions are more favorable. Moreover, coal mining is a relatively skilled activity and miners require several years of experience before they become fully productive.

Equipment and materials supply adjusts relatively quickly. Although short-run constraints in the equipment and materials input markets have occurred, they have not lasted more than two or three years. This adjustment time is much faster than the five- to eight-year lead time for equipment that industry sources feared in 1975.

Coal quality adjusts to market conditions. Coal is a heterogeneous commodity and users place values on its various attributes. The ability of utility boilers to accept relatively low grades of coal has extended usable eastern reserves and made exploitation of western reserves more feasible. It has also prevented significant long-run price increases that otherwise might have been caused by depletion of higher quality coal. The historical evidence also demonstrates a short-run response to tight markets: The average quality of coal shipped in tight markets tends to decline because the coal has not been properly prepared.

In the long run, producers have some flexibility in choosing among technologies. By virtue of mine locations in various reserves and because of some choices in mining methods, producers can vary somewhat the mix of labor and capital in mines. As reserves are depleted and work rules negotiated, these choices become more limited, and the options open to the producer to change the mix depend largely on using currently untested or undeveloped methods.

Changes in relative input factor prices affect labor productivity. Owing to some available flexibility in the labor-capital input mix, higher wage rates can be offset to some extent by varying the mix in a way that increases output per worker.

The coal industry has had a good record of technological change. Up to 1969, the advances resulting from new methods, more productive equipment, and new materials were steady in the coal industry. This trend contributed to the consistent increase in productivity observed in the industry.

Wage rates are affected by coal market conditions. There are two mechanisms that cause this behavior: The labor market reacts like other markets in that increased demand for labor in the face of labor supply constraints allows for higher negotiated settlements; workers negotiate for wages that tend to cause the price of coal to rise to the level of prices for alternative fuels. At present there is no unique and well-specified model of wage determination in the coal industry.

Market conventions arise to avert risk. To ensure continued supplies, utilities and other large users sought long-term contracts and backward integration into reserves and mining. The introduction of long-term contracts was welcomed by coal operators to ensure continued demand for output from new mines. During the 1960s, the expected rate of return on a mining project with a long-term contract was 5–8% less than a similar operation for coal destined to be sold on the open market.

Market conventions reinforce cost-based pricing and lead to lower average cost of delivered coal. Long-term contracts allow unit trains, lower transaction costs, and better integration of minimum-cost extraction rates with deliveries. All these factors have lowered delivered prices.

Government intervention has tended to increase mining costs and uncertainty. The effects of the Federal Coal Mine Health and Safety Act and environmental controls on mining have increased the average cost of mining. The environmental impact statement requirements on surface mining have decreased supply responsiveness and thereby increased short-run marginal costs, as have moratoria on leasing of federal lands. Sulfur emission controls on stationary sources have increased the risks of opening high-sulfur coal mines.

Interregional competition has increased. The lowering of transportation costs in relation to mining costs and the increased demand for low-sulfur coal have caused increased regional competition. Increased regional competition has not had a large impact on coal prices in the Midwest and East because competition within regions has forced long-run prices to move toward mining costs.

Transportation rates are affected by market conditions. There has been some flexibility in the setting of unit train rates. Evidence suggests that the larger the number of fuel and transportation options available to buyers, the lower are transportation rates.

Resource depletion has had only marginal and local effects. Resource depletion has affected the cost of mining some high-quality grades of coal in the East and has affected the availability of surface-mined coal in both the East and Midwest. However, resource exhaustion has not had a major impact on the cost of either deep-mined coal or surface-mined coal in the West. These mines lead in long-run price determination, and hence depletion has had little impact on long-run price formation. The decline in strippable reserves east of the Mississippi has decreased short-run supply responsiveness.

Uranium

The history of uranium supply suggests that producers respond fairly rapidly to changes in prices and in expectations about prices.

Early supply response to AEC stimulus. In 1951–1956, the foundations of the industry were built with high prices offered by AEC. Indeed, AEC either overestimated military demand or underestimated the supply elasticity. During these years the technological improvements in exploration, mining, and milling brought reductions in cost to offset any pressures for cost increases from rising factor prices. AEC was able to reduce new contract prices and still encourage exploration and entry into mining and milling. A price of $3/kg ($8/lb) was announced in May 1956 to take effect in 1962, and the industry showed strong signs of continuing expansion.

Initial supply response to private demand. After the mid-1960s, expectations about the development of the private market caused the market to expand, even without strong expectations that prices would rise substantially above the $3/kg ($8/lb) the AEC was paying through 1968. This is a deceptive period, for large reserves had been discovered prior to AEC's decision to confine procurement to reserves developed before November 1958. These deposits contained fairly low-cost reserves which, in the absence of AEC policy, might have been developed more rapidly in the late 1950s and early 1960s. Nonetheless, reserves grew. New entrants and existing firms planned expansions in mining and milling capacity, although in some cases these were ultimately cancelled or delayed as demand failed to develop.

Recent supply response. Since the end of 1972, the producers have followed the pattern of the two earlier expansion periods. Exploration has increased, new mines and mills have been announced, and there has been entry by new firms—and in a few cases, reentry by firms that had previously engaged in one or more stages of production of U_3O_8.

Possibility of periods of excess supply in the future. In the past, producers expanded capacity rapidly and then faced market demands that turned out to be insensitive to falling prices. In the first case, AEC maintained the price at $3/kg ($8/lb) from 1962 through 1968 but would not buy all the output that was profitable at that price. In the second case, after the initial promises of commercial demand proved illusory, falling prices coincided with the beginning of reactor delays, rising mining costs, short-run contracting preferences by utilities, and a reactor manufacturer willing to sell short at current U_3O_8 prices. In the future, long-term contracts may tie capacity plans more closely to U_3O_8 demands. However, if exploration efforts produce large additions to reserves or if demand forecasts are sufficiently revised downward, another period of excess supply might develop. This possibility has recently been raised in ERDA's public statements. For instance, a recent ERDA study suggests that attainable production capacity may exceed U_3O_8 requirements until the 1990s.

Special short-term market forces. A great amount of detail about price formation in the uranium industry is given in the report (EPRI EA-498), including Westinghouse Electric Corp.'s announcement that it thought the U.S. Uniform Commercial Code relieved it from responsibility of meeting its contracts. However, CRA noted that allegations of price-fixing activity by domestic procedures in the 1970s were beyond the scope of this investigation, particularly since it was the subject of current litigation. Also, CRA points out that whatever the true behavior of uranium producers in the mid-1970s, when predicting longer-term supply behavior it is unreasonable to project with the assumption of a permanent cartel. *Project Manager: Thomas Browne*

REGIONAL ELECTRIC UTILITY OPERATIONS MODEL

General Electric Co. has recently developed for EPRI a model to simulate the operations of electric utilities on a regional scale. The model can deal with the data for a region the size of a power pool or a National Electric Reliability Council region. The model will aid EPRI planners in assessing regional and system impacts of alternative future loads, system configurations, new generating and energy storage technologies, operating constraints, and fuel prices and availabilities.

A conceptual view of the model is illustrated in Figure 1. The model is similar to existing industry models in that the operating costs, fuel consumption, environmental emissions, and generating system reliability information are determined by an hourly simulation, which recognizes a particular expansion plan, load forecast, and operating policies. Individual units are committed and dispatched after considering dollar costs or a weighted combination of dollar costs and environmental emissions.

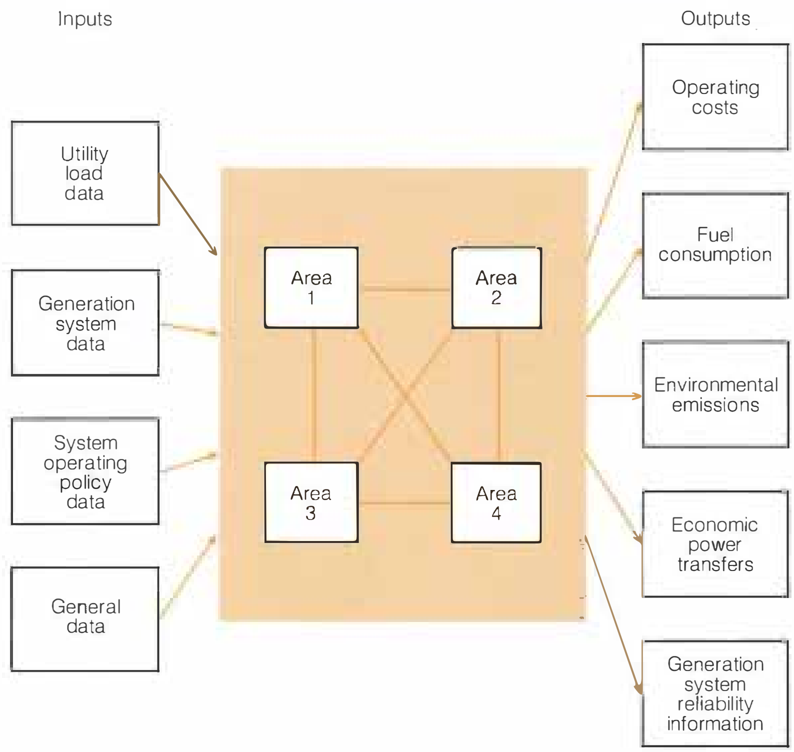
Unique to this model is a representation of up to four areas within a given region. Interconnections between areas are explicitly modeled to simulate the impact of finite power transfer limits on the generation system operations. Most models in use by industry are designed to simulate operations for a single utility. These models have been used to simulate multicompany power pool operations but with the assumption that tie constraints can be ignored or that power transfer capabilities between companies will not significantly influence overall production costs. General Electric has made some preliminary runs with the regional model and the results indicated that these assumptions may not be valid. It should be noted, however, that the regional model does not take into account transmission losses.

The model also has some interesting programming features. It is designed to strike a realistic balance between computer costs and simulation detail. Emphasis is placed on ease of data handling, so that sensitivity analysis can be performed efficiently and inexpensively. For example, load shapes can be easily modified by simply specifying alternative energy and demand growth rates. The model is split into two modules—data preparation and systems operations—so that data errors are detected and reported before a full simulation is run.

The full impact of the trade-off between computer costs and simulation detail on the quality of the model is yet to be determined. General Electric has made some test runs on the regional operations model and on another of their proprietary models. According to General Electric, the differences in results were negligible.

The model will undergo further testing and development at EPRI, General Electric, and the New York Power Pool (NYPP), each of which has a running version of the model. EPRI will test the model against established industry models by using capacity expansion scenarios developed on EPRI's representative (synthetic) utilities, which are used for

Figure 1 Conceptual view of regional electric utility operations model shows its unique capability of representing up to four areas in a given region and its similarity to existing industry models in that operating costs, fuel consumption, environmental emissions, and generating system reliability are determined by hourly simulation.



technology evaluation. The model will also be used to test the sensitivity of these expansion plans to alternative load shapes and fuel prices.

General Electric has jointly funded the development of the model with EPRI and has made the model commercially available on its Mark III Information Services Network.

NYPP, which has long used General Electric's planning programs, has worked with EPRI and General Electric throughout the project, reviewing progress and offering advice. In the process, NYPP has established an important link between EPRI-sponsored research and industry needs. NYPP has indicated that the model could play a major role in its planning efforts. The pool will scale down the current version of the model for planning purposes and use the model to conduct extensive sensitivity analysis on its current expansion plans.

NYPP is also participating in the empirical test of linking planning models to economic models (RP1056). The project is intended to determine the feasibility of using a specific method (devised by James Griffin of the University of Houston) for linking an engineering process model of electric utilities to a large-scale economic model. Griffin's method involves the generation of cost data. These data will be derived from the regional operations model and will help determine whether the model can be used, together with Griffin's procedure, to develop an engineering-based model of the electric utility industry.

An EPRI report describing the model, its use, and case studies will be available by November 1977. The model is available to electric utilities from EPRI. *Project Manager: Jerome J. Karaganis*

R&D Status Report
FOSSIL FUEL AND ADVANCED SYSTEMS DIVISION

Richard E. Balzhiser, Director

FOSSIL PLANT PERFORMANCE AND RELIABILITY

Although this program is little over a year old (EPRI JOURNAL, November 1976, pp. 25–26), it is firmly established with both the Fossil Fuel Task Force and the EEI Prime Movers Committee, which represents an important sector of the utility industry. Two presentations have been made to that committee: the first by Donald Anson (EPRI) and Elemer Makay (Energy Research & Consultants Corp.) on boiler feed pump problems and the second by Kenneth Medearis (Kenneth Medearis Associates) on foundation-related vibration problems in rotating machinery. The interest engendered by these activities has led to a close working relationship of mutual benefit to EPRI and its member utilities, and further presentations on EPRI programs are planned.

There are now 20 projects under way or being negotiated, some of them jointly funded with the Nuclear Power Division. Work completed this year includes:

- A review of the findings of six regional meetings on utility plant availability (EPRI FP-422-SR)
- A study of condenser structural design concepts (RP372, EPRI FP-507, forthcoming)
- A study of boiler feed pump problems (RP641, report in final draft)
- The laboratory development of a high-strength, high-toughness austenitic alloy for generator end rings (RP636, report in preparation)
- A review, with the Nuclear Power Division, of condenser failures (RP642-1, EPRI NP-481)
- A study of the application of availability engineering concepts to power plants (TPS76-662, EPRI NP-493, forthcoming)

Steam turbines

The major problem in large steam turbines is blade failure in the low-pressure rows. These blades operate at rotational speeds above that which corresponds to their natural vibration frequency and are thus subject to fatigue, as well as to high levels of steady stress. A further contribution to the dynamic loading on the blades may come from unsteady flow caused by fluctuations in the steam condensation process in the blade passages. Even with steam of high initial purity, salts separate as the pressure drops and can cause local corrosion where they concentrate. These salts lower the fatigue resistance of the blades.

These factors are being studied in this program, the objective of which is to provide data that can be used by utilities in specifying inspection routines, operating conditions, and materials and reliability levels in new plants and by vendors in meeting those specifications. The major effort is a study of corrosion fatigue by Westinghouse Electric Corp. (RP912). This includes an extensive review of data on steam and water chemistry. Initially, the relative susceptibility of a range of materials will be determined in atmospheres of steam with different controlled impurity levels. Long-term fatigue testing (to 10^8 cycles) will be carried out under selected conditions based on the initial test matrix. This project is being coordinated with others related to steam chemistry in the Nuclear Power Division.

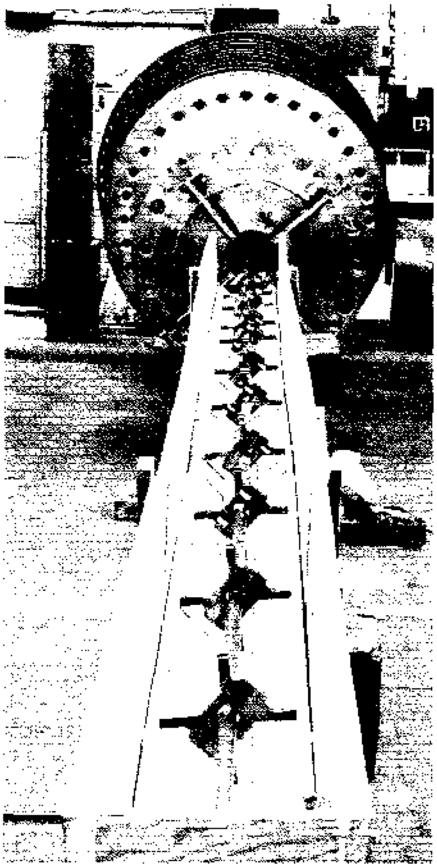
Condensation phenomena in expanding steam are being studied by General Electric Co. (RP735). The project has required development of special optical instrumentation for measuring drop size. In the condensation experiments, steam is allowed to expand at controlled rates, simulating conditions in a steam turbine. Pressure and temperature are measured. The initiation of condensation is observed optically, and the drop size and concentration of the water are measured continuously. The influence of steam impurities on the condensation process will be studied to see if there are measurable seeding effects.

Cyclic operation

Discussions at task force meetings, in the EEI Prime Movers Committee, and at a recent EPRI workshop on turbine reliability have revealed a general concern for the reliability of large steam electric plants when subjected to cyclic operation. This imposes temperature cycles on the turbine rotor and both temperature and mechanical stress cycles on the turbine casing and chest. These can cause creep and low-cycle fatigue damage, which could lead to catastrophic failures. Boiler pressure parts experience similar effects. Analytic techniques are needed to determine startup and operating conditions that will minimize the risk of damage, but direct knowledge of turbine metal temperatures, especially in the rotor bore, is limited. Boiler control techniques, such as superheater bypasses for steam temperature control, are being advocated as means to reduce the variations experienced by the turbine.

EPRI is funding a major experiment by Westinghouse Electric Corp., Babcock and Wilcox Co., and Commonwealth Edison Co. (RP911). The objective is to determine metal temperatures, including those in the rotor bore, under a variety of possible controlled startup cycles (Figure 1). The boiler and turbine for the utility's Collins No. 5 unit, now under construction, incorporates instrumentation for measuring relative movements and metal temperatures during startup cycles. Signals will be digitized and transmitted by telemetry to a fixed station near the turbine coupling. Observations will be compared with predictions to verify and improve predictive methods now being used. Improved

Figure 1 Turbine rotor bore temperatures—an index of material stress and creep during cyclic operation—are being measured by thermocouples mounted along this "spider" devised by the contractors. Thermocouple leads pass through radial grooves (X pattern on face of rotor) and terminate at radio transmitters in the rotor flange. A fixed antenna surrounding the flange picks off the digitized temperature data for recording and analysis.



confidence in these methods will permit more exact prediction of rotor life and the development of more economical startup procedures, without prejudice to reliability.

Further work related to plants not designed for cyclic operation is being considered to provide shorter-term data in this important area.

Boiler tube failure

A study by Foster Wheeler Energy Corp. is addressing the resistance of superheater and reheater alloys to scaling by steam and synthetic coal ash (RP644). Other mechanisms contributing to failure are mechanical stresses imposed by both internal pressure and external restraints, overheating from poor circulation or hot gas distribution, internal pitting, and fatigue. Bids have been received for a study to determine the relative importance of these and other causes of failure. However, it is clear that internal scaling deserves urgent attention because it also leads to rapid erosion of valve and turbine components by the exfoliated scale. This causes a drop in turbine efficiency and heavy maintenance.

The Foster Wheeler study has shown, as expected, that scale exfoliation occurs mainly during major temperature changes at startup or shutdown. There is evidence that the nature and adherence of scale can be influenced by conditioning processes and by exposure to hot water at about 316°C (600°F) before operation. Conditioning processes may be modified by control of pH and O_2 content, or perhaps by the deliberate addition of chemicals. Evidence of the importance of conditioning comes from experience in Europe and elsewhere. In England, because of a special concern for oxidation control in nuclear plants, the Central Electricity Generating Board (CEGB) has carried out extensive studies. Much of that experience will be available through an EPRI-funded study (TPS655), to be reported in the near future.

It is likely that a survey of boiler preservice cleaning, startup, and operation practices may contribute to the amelioration of the exfoliation problem, and this will be considered when the CEGB report appears.

Monitoring plant condition

Experimental work just commencing at New England Power Co.'s Brayton Point plant will soon be yielding data on the possibilities of using modern signal processing technology to identify plant problems at an early stage. The objective is to provide means of avoiding forced outages and to substitute scheduled maintenance. The experiment extends the well-known vibration-signature technique by using high-frequency (100-kHz and above) noise emissions on both discrete and continuous bases. In the past few months discussions have been held with the engineering staffs of Exxon Research and Engineering Co., and Radian Corp., who are either using or investigating similar applications, and there is a prospect of rapid development in this area.

In the specialized application of detecting water induction into steam turbines, Westinghouse Electric Corp. has demonstrated three possible techniques in the laboratory and will investigate their reliability on operating turbines (RP637). Little is known about minor cases of water induction, although those sufficiently serious to lead to turbine damage are documented. Service testing of detection devices will show whether minor or incipient incidents are more common than is generally supposed.

Donald Anson managed this program from its inception until mid-July. On loan from CEGB, he completed his term with EPRI and has taken a new position with TVA. *Program Manager: David Poole*

CLEAN LIQUID AND SOLID FUELS

Methanol is a prominent candidate as an ultraclean liquid fuel. It can be produced from coal by available technology, though the cost may be too high to compete with petroleum today and with other synthetic fuels in the future. This is by no means certain, however; it depends on the world fuel supply and the degree of success in development of alternative synthetic fuels. The EPRI methanol subprogram therefore has three main activities: keeping abreast of the state of the art; developing improvements that can be readily incorporated into commercial practice; and developing substantially different and improved—but longer-range—technology that offers significant economic incentive.

Methanol would probably be an excellent fuel for combustion turbines. A short test has been conducted at Florida Power & Light Co. in which methanol was compared with No. 2 distillate. Substantially reduced NO_x emissions were reported for methanol. Longer tests are required to make a more complete comparison not only of emissions but of operating and handling differences and turbine wear.

On the other hand, methanol could not be directly substituted for petroleum distillates, though conversion problems are not insurmountable. It has only half the heating value (Btu/gallon) and would require larger storage and pumping capacity. Methanol is toxic and is more volatile than distillate fuel. For example, the OSHA 8-hour standard for methanol in air is 200 ppm compared with 500 ppm for petroleum naphtha.

Marketed today as a chemical, methanol is produced at the rate of about 1×10^9 gallons annually. (This would fuel about 500 MW of continuous power generation.) It is formed from the reaction of carbon monoxide and hydrogen (synthesis gas) over a suitable catalyst. In current commercial practice, synthesis gas is prepared by steam-reforming of natural gas. The stoichiometry is summarized as:

Methanol synthesis $CO + 2H_2 \leftrightarrows CH_3OH$

Steam-methane reforming

$$CH_4 + H_2O \leftrightarrows CO + 3H_2$$

In the future, gasification of coal with steam and oxygen will replace steam-methane reforming as a source of synthesis gas. Commercial coal gasification processes exist today, and several other gasifiers are close to commercial availability. Coal-derived synthesis gas can be used as a direct substitute for steam-methane reformed gas and does not require changes in the methane process.

Methanol differs from other synthetic liquids in that it is made from products of coal gasification from which all potential pollutants have been removed by conventional purification systems. It is free from sulfur, nitrogen, and minerals.

Produced from coal by state-of-the-art technology, methanol is quite expensive —the cost estimate is in the range of \$6–\$7/10^6 Btu (based on 50% debt, 50% equity with 8% bond interest, and 12% return on equity in constant 1977 dollars). Most of this cost is for coal gasification and gas cleanup. Only about 10% of the cost of a coal-based methanol plant is for methanol synthesis equipment. Methanol costs using different gasifiers under development are being estimated by The Ralph M. Parsons Co. (RP715).

A major cost associated with the methanol process derives from the low thermal efficiency of converting coal to methanol. For a typical energy self-sufficient plant, only 50–60% of the feed coal heating value winds up in methanol. In the methanol synthesis loop itself, the theoretical limit of energy recovery from a stoichiometric reaction is such that only 85% of the synthesis gas energy can be recovered as methanol. The rest is liberated as heat of reaction during the synthesis step. Until recently there was little incentive to recover this energy since the fuel (natural gas) represented only a small component of product cost.

Chem Systems Inc. is developing a new methanol synthesis reactor in which the heat of reaction is absorbed by an inert oil that circulates through the reactor (RP317). This type of reactor system is known as an ebullated bed (conventional methanol synthesis is carried out in a fixed catalyst bed). An additional benefit in using the liquid heat carrier is that it allows a lower temperature rise and correspondingly favorable chemical equilibrium at the reactor exit. Furthermore, since large amounts of recycle gas are not required to limit the temperature rise in the reactor (as is done in conventional processes), the methanol concentration in the exit gas is several times higher than from fixed-bed systems. As a result, the conversion (per pass) of feed coal to methanol is higher.

The new process has been operated in bench-scale and process-development units. The only remaining problem is to develop a catalyst formulation suitable for the ebullated bed, with satisfactory activity and life. It is likely that this will be accomplished in 1978. Economic studies have shown that use of the liquid-phase synthesis reactor could lower the cost of methanol by about 10%.

Clean distillate fuel

EPRI has devoted substantial effort to the study of a synergistic combination of hydrogenation liquefaction of coal and methanol synthesis. Discovered by EPRI staff members, this process configuration has been designated the clean distillate fuels (CDF) process. During work on solvent-refined coal (SRC) and gasification of coal liquefaction vacuum bottoms by partial oxidation (RP714), it was observed that an SRC process can be operated under conditions that produce a high yield of light distillates, together with vacuum bottoms containing the SRC product and the coal mineral matter. Rather than separating the SRC from the mineral matter (as is done in the conventional SRC process), the vacuum bottoms are fed to a partial oxidation gasifier to produce synthesis gas, which is then catalyzed to methanol. The combined process produces about equal Btu quantities of methanol and synthetic petroleum distillate. When and synthetic petroleum distillate. When western subbituminous coal is fed, the synthetic distillate is of high quality (less than 0.3% sulfur and nitrogen).

The CDF process has several synergistic benefits over separate production of synthetic distillates and methanol and it is more efficient. Some of the benefits are:

- Vacuum bottoms are a superior gasifier feedstock compared with coal (for a high-pressure partial oxidation gasifier).
- Gas cleanup for the SRC and gasification sections can be integrated.
- The hydrogenation liquefier need be operated only for partial conversion to distillates.
- Heat recovery and internal plant fuel requirements can be efficiently combined.

C. F. Braun & Co. is working on an economic evaluation of the CDF process (RP832-1). Results to date show that the fuel (about 60% methanol and 40% distillates by heating value) would have an equivalent price of about \$4.50/10^6 Btu. This is substantially less than for separate production of methanol and synthetic distillate.

Foster Wheeler Energy Corp. has studied the cost of a 25-t/d pilot plant for demonstration of the CDF process (RP916). It is estimated that such a plant would cost \$12 million to construct (1977 dollars). *Project Manager: Howard Lebowitz*

Superconductivity in Power Generation

by Mario Rabinowitz

A superconducting rotor means less iron, higher voltage, greater power density. Feasibility studies point to an ac generator that is thus smaller, lighter, more efficient, and less expensive, even at today's 1000-MVA rating. ▫ An EPRI technical article

The superconducting ac generator may well be the first large-scale commercial application of superconductivity. Such a machine should be able to convert mechanical energy to electric energy more efficiently and with greater economy of weight and volume than any other method extant or conceived. These advantages can foreseeably accrue at today's scale of output—1000 MVA—with the added potential of operation at transmission line voltage level and greater system stability. The prospect for the superconducting generator has moved from that of mere speculation to definitive design feasibility studies by Westinghouse Electric Corp. and General Electric Co. under EPRI sponsorship.

U.S. system potential

The cost of power generation is the incentive for R&D investment in a superconducting generator, and a 0.5% increase in efficiency (equivalent to an impressive 50% reduction of losses) more than provides justification. Approximate measures of U.S. utility plant expansion and cost illustrate this.

From 1960 to 1970 the capacity of the electric power industry almost doubled—from 175 to 325 GVA. By the end of 1975 it had reached 474 GVA. To meet an estimated demand of 1200–1700 GVA before the year 2000, utilities will have to install at least an additional 700 GVA of capacity. At an average capital cost of $800/kW for power plants, $560 billion must be invested to meet this demand—including $7 billion (at $10/kVA) for the generators alone.

If the increased generation demand could be met by superconducting machines, then (at $0.03/kWh, 0.9 power factor, and 80% availability) the annual savings would be $660 million. In just 11 years that is more than the required capital investment for the generators, which can reasonably be assumed to have a 25-yr life. The total money spent for research to date is infinitesimal by comparison.

How and why superconducting generator designs should be beneficial in power generation—and produce savings even if more modestly deployed—depends on the attributes of materials in the superconducting temperature range and how they can be exploited in the electrical design of an ac generator with a superconducting rotor.

High-voltage possibilities

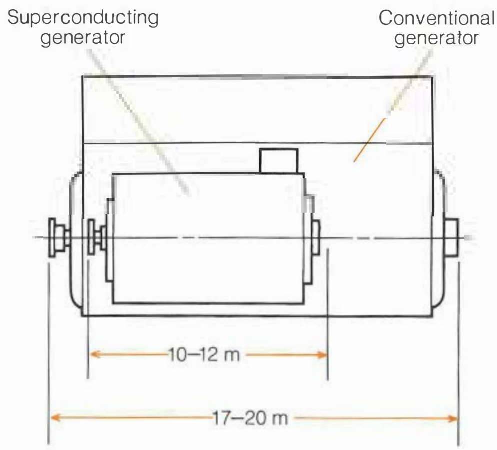
The high flux density produced by a superconducting rotor field winding permits a great reduction of iron in both the rotor and the stator. This introduces degrees of freedom not previously possible in generator design. Elimination of iron in the stator allows an increased density of turns in the armature and also reduces insulation requirements, both changes making for better use of space and materials. When grounded iron is removed from these windings, less insulation is needed between adjacent bars. Full interphase insulation is still needed between end winding groups, but the reorganized windings and insulation (made possible by the absence of the stator's iron teeth) permit reduced insulation stress and, in turn, higher voltage operation.

Even doubling the present upper limit of 35 kV for conventional generators would result in only limited gains. The real opportunity afforded by the superconducting generator is its potential for generation at full-line voltage—230 kV, 500 kV, or even higher. This would remove the necessity for a step-up transformer, resulting in simplification of the central station, a probable increase in reliability, and savings in capital and operating expense for either ac or dc power stations.

Stored-field rotor

At high field levels, a superconducting rotor and elimination of iron appear most promising. For special applications where field variation is unnecessary (where load is approximately constant or where terminal voltage may drop with increased load), it may be possible to use a hybrid, stored-field rotor with a normal rotor coil surrounded by a superconducting shell. This would eliminate many of the problems of winding a superconducting coil and of losses due to wire motion in the coil. It has been demonstrated (*1*) that a magnetic field of any configuration can be stably stored in a simple superconducting cylinder. It is therefore possible to pulse on the normal coil with large overcurrents and then "trap" this field in the superconducting cylinder that

Mario Rabinowitz is the senior scientist in EPRI's Electrical Systems Division.



Size advantage of a superconducting generator is suggested by this schematic comparison of 1200-MVA machines. Smaller size implies economies in generator materials and resultant savings in weight, foundation requirements, and plant structure. The rectangular envelope above each unit represents its hydrogen circulation system.

acts as the rotor field. To date, a uniform dipole field as large as 22,400 Oe has been stored in a cylinder of superconductor thickness less than 1 mm, and much larger fields can be trapped.

Even in metals that exhibit superconductivity, two characteristics limit the phenomenon. One, of course, is a temperature limit, T_c, above which the metal is not superconductive. The other is the second critical field, H_{c2}, the magnitude of which is a function of T.

The A-15, beta-tungsten structure superconductors are brittle, as are many other high-H_{c2} materials. Because of the high H_{c2} and concomitantly high critical-current density of these materials at high fields, they are quite desirable for high-field electromagnets in such applications as generator rotors, nuclear fusion, and magnetohydrodynamics. Table 1 characterizes these exceptional superconductors, which could easily be incorporated in a stored-field device but would be very difficult to make into a coil. By contrast, NbTi, the wire superconductor most used today, has a T_c of only 9.5 K and H_{c2} of only 12 T. Although multifilamentary Nb_3SN wire is now commercially available, its long-term performance in wire form remains to be demonstrated.

Since the stored field does not require

Table 1
EXCEPTIONAL SUPERCONDUCTORS FOR GENERATOR APPLICATION

Material	*Critical Temperature* T_c *(K)*	*Second Critical Field* H_{c2} *(at 4.2 K)*
Nb_3Ge	23	37
$Nb_3(Al, Ge)$	21	41
Nb_3Ga	20.3	33
Nb_3Al	18.9	30
Nb_3Sn	18.1	22
V_3Ga	15–16.8	23
$PbMo_{5.1}S_6$	14.6	50

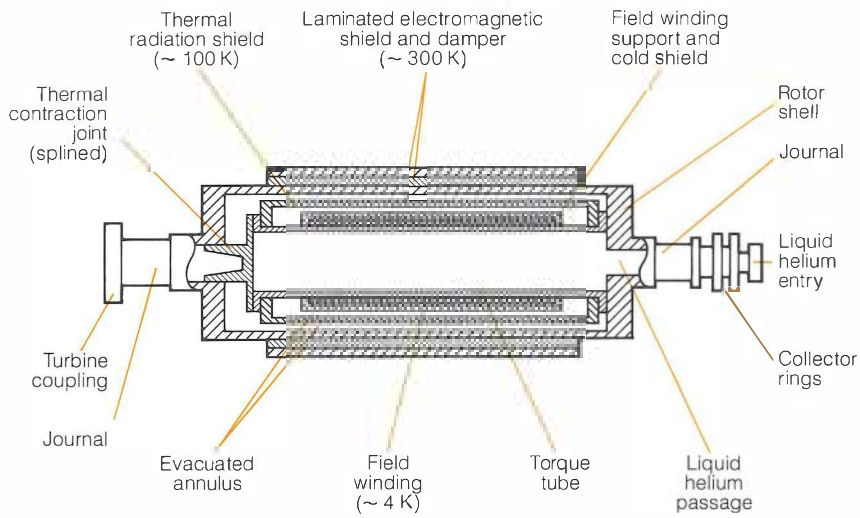
continuity of the superconductor, hysteresis and other power losses (due to time-varying harmonics that penetrate the shield) can be minimized by segregating the superconductor over the surface of the rotor. In a multilayered structure, alternate layers of superconducting gridwork (sandwiched between normal conductors) can be displaced with respect to each other so that the entire rotor surface is covered by superconductor, even though it is discontinuous in any layer. The field will decay due to power losses that can be minimized. The normal rotor coil can be pulsed on periodically to restore the field level or to produce discrete field changes that may be needed to follow occasional load variations. The stored field can be de-energized more rapidly than any other rotor field because there are no wires to melt or insulation to spark through during intervals of high di/dt.

It must be understood that the magnetic field in a generator is not intended to do work. The rotor field does essentially no work as long as there is negligible time variation of the field. Thus, the generator field serves only as a vehicle to convert mechanical power into electric power; its purpose is to couple the mechanical energy to the electrons in the armature. Consider the equation

$$\text{Work} = \int \vec{F} \cdot \vec{ds} = \int (q\vec{v} \times \vec{B}) \cdot (\vec{v}\, dt) = 0$$

where F = magnetic force
s = displacement of electric charge
q = electric charge
B = flux density
v = charge velocity
t = time

Three cylindrical shields and two evacuated annular chambers isolate and maintain the critical low-temperature regime of this representative superconducting rotor. Interestingly, axial contraction of the rotor at superconducting temperature should be less than the expansion that results from heat created in conventional rotor operation.



This relationship shows that the static (in time) field does no work because the displacement of the electric charge is always at 90° with respect to the magnetic force. Thus, one measure of the efficacy of the conversion process is the compactness of the device, as indicated by the power density. It should not be surprising that the power density depends strongly on B since the pressure or energy density of the magnetic field is proportional to B^2.

Increased system stability

The potential for increased system stability intrinsic to a superconducting generator is of great importance. When a system (generator—grid load) is perturbed electrically or mechanically, the resulting transient is oscillatory. If the oscillations damp out to the original or a new steady-state operating condition, the system is stable. But if it becomes unstable, protective equipment is required to shed load and disconnect generators from the grid. A perturbation can be a major disturbance, such as the loss of a generator, a fault, the loss of a line, or a combination of such events. It may also be a small, slow load change or a quick, random load change occurring under normal operating conditions.

In general, the lower the generator reactance, the more stable the system. For a superconducting generator, the synchronous reactance is about one-fourth that of a conventional machine having a similar rating, resulting in a steady-state stability limit as much as four times greater when the transmission line reactance is relatively small. This virtually eliminates the steady-state stability limit, allowing the generator to operate over a wide range in power factor. A superconducting machine is thus capable of operating more underexcited or on a weaker power system than a conventional unit.

In a conventional generator, subtransient reactance is not an important stability factor because the time constant associated with it (~0.04 s) is so small. Time constants are a function of machine damping and are independent of reactances. However, in most superconducting machine designs, shielding and damping functions are combined. Good shielding implies poor damping (long time constant), and vice versa. Subtransient reactance affects the stability of a superconducting generator because the subtransient time constant can be as long as ~0.2 s (about five times as long as in a conventional machine). Thus, the transient stability of a superconducting machine—its ability to withstand transient disturbances—is affected by both the subtransient and transient reactances, as well as by the rotor inertia. Despite the lower rotor inertia of a superconducting machine, which detracts from stability, transient and subtransient reactances can be reduced sufficiently to yield a net improvement.

These changes also reduce terminal voltage dip during load switching. Further, the lower their values, the longer will be the critical-fault clearing time of the unit (all other system parameters remaining the same). A long time is needed to allow for relaying, for primary circuit breaker operation, and (if necessary) for bringing in backup circuit breakers in case of failure of the primary breakers.

Analytic perspectives

Describing the electric performance characteristics and relationships of a superconducting generator is important. But understanding why those relationships are possible, what limitations may arise in generator use, and some of the improvements that can be sought also calls for discussion.

Power Density This is a key functional attribute, which is related to the magnetic flux density. A superconducting field winding in the rotor not only eliminates ohmic losses but also permits much higher magnetic fields than are possible in conventional machines that rely on low-reluctance magnetic circuits. The former may easily operate up to 10 T, but the latter are limited to 2 T by the saturation field of iron. The significance of this difference becomes apparent when power densities are compared for superconducting and conventional generator concepts.

Power density may be maximized by optimizing the combination of magnetic, electric, and mechanical components. The essential parameters can be related without belaboring detail. Neglecting friction, the torque (τ) required to turn the rotor is

$$\tau \propto p\phi NI$$

where p = number of phases
ϕ = excitation flux of the rotor
N = number of turns in the armature, and
I = armature current

The generated (open-circuit) voltage (V) is

$$V \propto N\frac{d\phi}{dt} \propto N\phi\omega \propto NB\ell D\omega$$

where ω = angular velocity of the rotor
B = average magnetic flux density at the armature winding (related to field at the rotor)
ℓ = active length of the machine (related to rotor length), and
D = diameter of the armature winding

The mechanical power input (P) is

$$P = \tau\omega \propto p\phi NI\omega$$

Neglecting the internal voltage drop due to synchronous impedance, the electric power output (also P) is

$$P = pVI \propto p(N\phi\omega)I \propto p(NB\ell D\omega)I$$

Neglecting friction losses also, these two expressions of P are the same. The power density is thus

$$P/v \propto BI(N/D)\omega$$

where v = volume of the machine

Based on the last equation and the relationship $v \propto \ell D^2$, the power density varies directly as the first power of the flux density.

It is possible to do even better than this, depending on the specific current loading of the stator winding. Armature currents may be increased in proportion to the excitation field without reaching reactance values that limit stability. To determine the upper limit of power density, armature power loss and cooling restrictions may be neglected. In simplistic terms, the torque to rotate the rotor is

$$\tau \propto D \times (B^2 D\ell)$$

Power may then be expressed as

$$P = \tau\omega \propto B^2 D^2 \ell\omega$$

Power density thus is

$$P/v \propto B^2\omega$$

Now it is apparent that power density may go as high as the square of the average flux density at the armature. The limit may be the mechanical yield strength of structural materials (such as the damper shield) during short-circuit conditions.

Both increased flux density and reduced iron contribute to higher power density relative to either weight or volume. At ratings of 500–1200 MVA, a superconducting generator would be 25–50% of the weight and 30–50% of the volume of a conventional one. (Some of the imprecision relates to the range in choice of machine reactances.) These dramatic advantages of higher power density make rotating superconducting machines attractive.

Basic Limitations Iron is used in conventional rotating machinery to lower the reluctance of the magnetic circuit, to increase output, to reduce the necessary volume, and to decrease the power loss due to magnetizing currents. The magnetic flux density in a conventional generator is limited to less than 2 T because of the saturation of the iron. Because the generated voltage (V) is proportional to the time rate of change of flux ($d\phi/dt$) and because there are mechanical limits to rotational speed and saturation limits to flux density, sufficient flux to cut the armature windings and meet design goals must be provided volumetrically. This is done by using a field coil of considerable length and radius as the rotor. Its maximum diameter is determined by the angular velocity where stress due to centrifugal force exceeds yield stress. Since centrifugal force is proportional to mass, simple buttressing or reinforcement does little to extend the limit. Essentially, rotor rigidity is

$$\propto r^2\ell^{-3}$$

where r = rotor radius
ℓ = rotor length

Even if radius were not ultimately limited by centrifugal force, it would be constrained by transport facilities. So, a given rotor stiffness cannot be maintained simply by increasing radius faster than length. Also, as length increases, the natural frequency decreases; with this comes a decrease in the first critical speed and an increase in the number of critical speeds. These require more stringent and sophisticated balancing. For an end-supported rotor, therefore, flexure and vibration severely limit length.

Centrifugal force and generated voltage are both related to rotor radius and angular velocity; that is $F \propto \omega^2 r$ and $V \propto N\omega r$. Therefore, the limitation of material strength can be met (for a given voltage) by increasing radius and decreasing angular speed. Historical development has thus produced machines that are bigger, more cumbersome, more expensive, and more difficult to transport.

Potential Improvements The foregoing analysis suggests at least five ways in which a superconducting generator might be better, smaller, lighter, and less expensive than a conventional one:

- By eliminating much of the iron
- By increasing the working magnetic flux density in the armature
- By reducing the excitation losses
- By reducing the centrifugal reaction force on the conductors in the rotor
- By reducing reactances for improved system stability

A potential sixth advantage, increased current density in a superconducting armature, remains a remote possibility because, at present, the ac losses and concomitant refrigeration requirement are too high.

Increased efficiency appears to be a clear-cut gain for a superconducting generator. Although a gain of only 0.5% appears small, it has a leverage factor of about 100 on overall plant capital cost. For a large generator, it can also be significant in terms of fuel and operating costs. A conventional 1200-MVA machine has an excitation loss of more than 5 MW, which far exceeds the combined excitation and refrigeration power required for a superconducting machine. The core, armature, excitation, bearing, and windage losses are calculable with reasonable confidence for both machines.

Armature ohmic loss can be reduced in proportion to length of winding. Higher flux density dictates the transposition and use of finer wires to reduce eddy-current losses. Stator-core-iron loss is reducible by eliminating more than 50% of the iron. Since high permeability and high saturation are no longer paramount, lower-loss steel may be used.

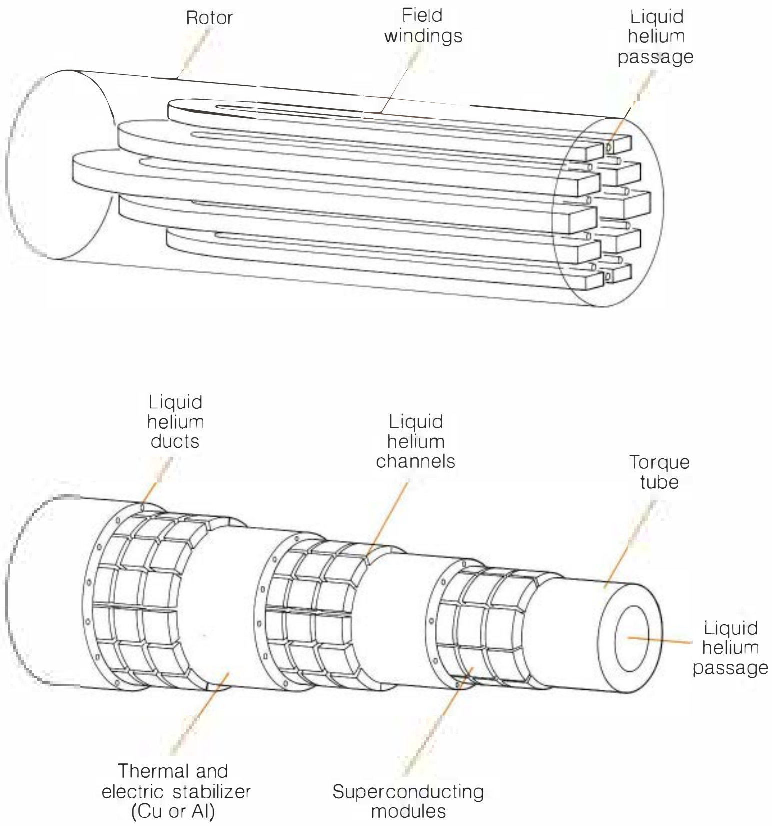
In commercial practice, bearing losses are omitted when citing generator efficiency. For a 1200-MVA unit these are 0.13% and are included among overall turbine-generator losses. Although the rotor may be reduced by as much as 75% in weight, only the nondrive end may be reduced substantially in dimension and loss. The drive-end bearing size and losses are dominated by turbine torque. So, at most, a gain of 0.07% is possible in this regard.

A conventional 1200-MVA machine has a windage loss of about 0.2%. Since the superconducting rotor has much less wind resistance (being smoother due to the shield, and also shorter and narrower), the windage loss can be reduced by an order of magnitude.

EPRI program potential

A well-designed superconducting generator will represent a beautiful optimization between competing and often conflicting electric, economic, thermal, reliability, and me-

Simplified schematic affords comparison of "racetrack" field windings and stored-field "shells" of two superconducting rotor concepts. The stored field may be induced by the stator or, in a hybrid design, by field windings inside the torque tube beneath the superconducting modules.



chanical requirements. Basically, thermal performance deteriorates as operating temperature is decreased, but electric performance improves. Electrical system stability and power density are increased at the expense of structural stability. Thermal isolation is improved at the expense of mechanical strength and vibration tolerance. Of course, the increased complexity of the advanced technology must not be allowed to compromise reliability. On the other hand, economics compromises everything.

EPRI's program features concurrent, sponsored research projects with Westinghouse Electric Corp. and General Electric Co. In designing these projects, it was decided that they should be independent and competitive and should involve power levels high enough to be meaningful for utility applications. Therefore, the objectives are to produce a detailed design for a 300-MVA superconducting generator and a less detailed conceptual design for a 1200-MVA unit. This will help determine at what power level the superconducting machine reaches economic parity. Going from state-of-the-art 5 MVA to 300 MVA is an enormous step, which many felt was too large to take. However, solutions to problems at 50 or 100 MVA may not be applicable at 300 MVA and higher. It is generally easier to scale down than to extrapolate a design. Related work at the Massachusetts Institute of Technology has been directed at a much lower power machine (~3 MVA) and at more advanced, higher-risk solutions to synchronous superconducting machine problems.

EPRI funded its projects at about $500,000 each, with effectively substantial cost sharing. Contract work started in September 1975 and is now completed. As the contractor's reports are being reviewed for publication, it is not premature to say that their findings look extremely promising.

Although the cost of an ac generator is relatively insignificant compared with the cost of an entire power plant, it may be considered the pivotal element. It not only dominates the electric aspects of the plant but can also influence capital costs. Even when refrigeration is included, an incremental decrease in losses of ~50% can be calculated for superconducting generators as compared with conventional generators. This is equivalent to the increased efficiency of ~0.5% suggested earlier. The output of the plant is thus increased by the same 0.5%. At approximate capital costs of $800/kW for plant and $10/kW for generators, the cost benefit is approximately 80 times the efficiency improvement. In other words, the leverage of capital funds spent on the generator alone is 80 times as effective as funds spent elsewhere in the plant to achieve the same improvement in overall efficiency.

The capital cost of a superconducting generator and its refrigeration may well be less than that of a conventional generator. Moreover, this does not include additional contingent savings, among which are other capital, financing, and operating costs. For example, a turbine-generator foundation may cost $25,000 per axial foot. Based on a reduction in length of 20 feet for a 1200-MVA superconducting generator, approximately $500,000 can be saved on the foundation. The turbine-generator building can also be shortened by 20 feet. At a cost of $35 per square foot, and assuming a width of 100 feet, the building foundation cost can be reduced by $570,000.

Testing for reliability

In light of soaring costs for energy and materials, the economic benefits may be greater than previously estimated. But even though the advantages of higher efficiency, reduced size and weight, lower capital cost, and greater stability may be realized in an ac superconducting generator, these must be weighed against a single factor—reliability. If the superconducting machine is less reliable than a conventional unit, even a few more days' outage per year could tilt the balance against it. It is a more complicated and more delicate machine than its rugged counterpart. In fact, part of its beauty

Table 2
1200-MVA GENERATOR COMPARISON

Characteristic	*Superconducting*	*Conventional*
Phase-to-phase voltage (kV)	26–500	26
Line current (kA)	26.6–1.4	26.6
Active length (m)	2.5–3.5	6–7
Total length (m)	10–12	17–20
Stator OD (m)	2.6	2.7
Rotor diameter (m)	1	1
Rotor length (m)	4	8–10
Synchronous reactance (per unit)	0.2–0.5	1.7–1.9
Transient reactance (per unit)	0.15–0.3	0.3–0.4
Subtransient reactance (per unit)	0.1–0.2	0.3
Field exciter power (kW)	6	5000
Generator weight (tons)	160–300	600–700
Total losses (MW)	5–7	10–15

stems from its achievement without recourse to brute force. It has the potential of solving problems for which the past response of "more and larger" is no longer adequate.

The reliability question can best be decided by prototype testing in a laboratory and on a utility system. This remains to be done. We should not shortchange the superconducting generator on the issue of reliability, because in some respects it may well have greater reliability than its counterpart, whose relative durability may only be virtual. For example, the temperature stability of the superconducting rotor during field changes (compared with the large temperature changes associated with varying ohmic heating in a conventional machine) means less wear on conductors and insulation. Interestingly, due to the reduced overall length for a large machine, the contraction of the rotor in cooling from ambient to helium temperature may be expected to be less than the expansion associated with the heating of a conventional rotor.

The next phase in development of a superconducting utility generator involves a multimillion-dollar construction and testing program. Much effort is going into the planning and preparation of this phase. EPRI has not yet decided the size of the generator; this may depend on the availability of a prime mover for utility testing. Another possibility is that for a relatively small incremental cost, we will build two superconducting machines. One could be operated as a motor to drive the other as a generator. Only a small prime mover would be needed for laboratory short-circuit and open-circuit testing.

Table 2 lists approximate sample parameters or characteristics by which a two-pole, three-phase, 1200-MVA superconducting generator may be compared with a conventional one, where both have 1080-MW rated power (0.9 power factor) at 60 Hz (3600 rpm).

The many advantages are clearly evident from the table. The feasibility has been reasonably well established. The technical and economic advantages are very attractive. We have reached a stage where the promise exceeds the limitations, and there is no question but that we continue to the next stage. It is increasingly apparent that superconducting technology can be made applicable for meeting many power-generating needs of U.S. utilities, not to mention those elsewhere in the world.

References

1. M. Rabinowitz, H. W. Arrowsmith, and S. D. Dahlgren. "Dependence of Maximum Trappable Field on Superconducting Nb_3Sn Cylinder Wall Thickness." *Applied Physics Letters 30,* 607 (June 1, 1977).

Historical background detailing the development of superconducting generators up to the present time can be found in the paper from which this article was adapted: M. Rabinowitz. "Cryogenic Power Generation." *Cryogenics 17,* 319 (June 1977).

New Technical Reports

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

Inquiries on technical content may be directed to the EPRI project manager named at the end of each summary: P.O. Box 10412, Palo Alto, California 94303; (415) 493-4800.

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ELECTRICAL SYSTEMS

Power system dynamic analysis: phase I

EL-484 Final Report (RP670-1)

The models required for power system dynamic analysis are growing larger and more complex. However, dynamic studies already require a significant portion of the computer capacity of electric power utilities. Thus, the industry must both reduce the cost of dynamic simulation without sacrificing reliability and allow for more realistic simulation through the use of more complex models.

This Boeing Computer Services, Inc., report concentrates on the analysis and selection of appropriate numeric methods for computer solution of the system dynamic performance. The fundamental characteristics of dynamic power system models were identified and related to candidate numeric methods. Extensive testing was performed on selected test cases to identify the best computation procedures for solving power system dynamic problems. The testing program not only performs transient stability computation but also analyzes the performance of the numeric methods.

Conclusions of this first phase include specific recommendations of integration methods, step size requirements, and algebraic solution methods that will provide the basis for a new industry standard transient stability program. Recommendations are also included that will be useful for improving the efficiency and reliability of existing stability codes with minimal changes required. *EPRI Project Managers: T. S. Yau and P. M. Anderson*

ENERGY ANALYSIS AND ENVIRONMENT

The effects of high-voltage transmission lines on honeybees: a feasibility study

EA-489 Final Report (TPS76-630)

The need increases for rigorous scientific studies of possible effects on living things of EHV transmission lines' electric and magnetic fields. This study by Bioconcern is part of EPRI's integrated program on biological effects of electric fields. It was designed as an initial feasibility study to establish an accurate scientific approach. The experimental design developed will be modified as necessary, in light of initial field tests, to yield accurate data. It serves as the framework for a three-year study, in which bees will be exposed to electromagnetic fields under a 765-kV line.

The honeybee was chosen as the test subject because the complex behavior of bees and the statistically valid numbers of individuals examined increase the probability of identifying subtle neurological influences or other obscure effects upon heredity, development, behavior, metabolism, or communication. Such information might pertain to higher animals but would be less easily detected. The parameters to be measured include colony population, honey stores, amount of acoustic noise generated by the bees, in-hive temperature, incidence of queen cell production, and tendency to swarm.

Accompanying dosimetric support includes in-hive electric field measurements, development of shielding to eliminate the electric field from selected colonies, analysis of the acoustic data, and periodic checks on the ambient electric field under the line and at the control site. *EPRI Project Manager: H. A. Kornberg*

FOSSIL FUEL AND ADVANCED SYSTEMS

Geothermal environmental baseline data acquisition, Heber Region, Imperial Valley, California

ER-352 Final Report (RP556)

EPRI has been studying the feasibility of a low-salinity hydrothermal demonstration plant as part of its Geothermal Program. The Heber area of the Imperial Valley was selected as one of the candidate geothermal reservoirs to be considered as a site for the demonstration plant. Documentation of the environmental conditions in the Heber area is required for assessment of environmental impacts of future development by design engineers and to meet regulatory requirements.

San Diego Gas & Electric Co. has managed an environmental baseline data acquisition program to compile available data on the environment of the Heber area. The program included a review of pertinent existing literature; interviews with academic, government, and private entities; field investigations; and meteorologic monitoring to collect primary data. Results of the data acquisition program are compiled in this report in terms of the physical, biological, and socioeconomic settings.

Primary conclusions drawn from the investigation suggest that sufficient data are available to make preliminary assessments of environmental impact of a geothermal project on the site. *EPRI Project Manager: P. N. LaMori*

Proceedings of the workshop on switching requirements and R&D for fusion reactors

ER-376-SR Special Report

An EPRI-sponsored workshop on electrical switch requirements and R&D for fusion applications took place in Palo Alto, California, March 24–26, 1976. Thirty-two participants attended from industry, government laboratories, universities, the Department of Defense, ERDA, and EPRI.

The workshop consisted of formal presentations, followed by open discussions. Topics ranged from illustrating the state of the art to defining reactor switching requirements and switch R&D requirements.

The material presented at the workshop, plus subsequent comments by the participants, is included in this report, which was prepared by the Department of Electrical Engineering, Texas Tech University. Specific switch requirements and switch capabilities are listed, along with an introductory bibliography on switching. A summary of the workshop discussions as well as suggestions for areas and directions of future R&D are given. Also included is a brief report on a related work shop, more limited in scope, which was held in Garmisch, Federal Republic of Germany, on June 19, 1976. *EPRI Project Manager: N. A. Amherd*

Conceptual design for a pilot-demonstration compressed air storage facility employing a solution-mined salt cavern

EM-391 Final Report (RP737-1)

Compressed air energy storage (CAES) is a system for electric utility application that permits the storage of energy generated during low-demand periods and the regeneration of that energy during peak demand periods. General Electric Co. completed a conceptual design for a CAES plant situated on the McIntosh salt dome in southwestern Alabama.

The plant has a peak turbine inlet pressure of 4 MPa (40 atm), with the peak air storage pressure ranging from 4.4 MPa (44 atm—constant pressure storage) to 8.7 MPa (86 atm—variable pressure storage). A weekly storage cycle is used, and power is generated at a rate of 800 MW for 2000 h/yr. The capital cost of these plants ranges from \$196 to \$200/kW (mid-1976). The fuel heat ranges from 4140 to 4330 Btu/kWh. Depending on the storage reservoir design, the system delivers between 1.15 and 1.39 kWh for each kWh of charging energy. Very few of the design parameters have been found to be site-specific, and this design may serve as a general example of a high-pressure CAES system.

A modification of these designs was developed for 500 hours of annual duty (peaking application). It would require a capital investment of about \$140/kW, with the same heat rates and charging energy ratios as the 2000-h designs.

The operating economics of a new method for computing the efficiency of CAES plants and of experiments that might be performed at a demonstration plant were evaluated.

For a substantial range of costs of charging power and premium fuel, CAES systems appear to be more economically favorable than gas turbines and other utility storage systems. At the conceptual level of these designs, no technical or environmental barrier to constructing these plants was found. *EPRI Project Manager: J. W. Pepper*

Closed-cycle, high-temperature central receiver concept for solar electric power

ER-403-SY Summary Report (RP377-1)

Boeing Engineering and Construction examined the technical feasibility of a high-temperature, gas-cooled central receiver for producing electric power from solar energy, using a closed Brayton helium cycle. Feasibility was examined in terms of system life, efficiency, cost, and technology requirements.

These considerations have been implemented in the conceptual design of a receiver for integration into a 100-MW solar plant. Thermal cycling tests simulating a 30-year lifetime of the receiver's heat exchangers at operational temperatures to 816°C (1500°F) were performed to select materials.

Performance and operational studies show the receiver operates simply and effectively over a wide range of environmental and operational conditions. All the required technology for receiver design and implementation currently exists. Preliminary design considerations were made for a 1-MW bench-model receiver to verify the full-scale receiver. Preliminary planning was developed for a 10-MW electrical pilot plant to follow the receiver verification.

The study also included system/subsystem definition for employing the central receiver design in a solar plant and predicting plant performance. Conceptual designs of several thermal energy storage devices were defined, integrated into plant performance and operational models, and evaluated with energy cost as the criteria. *EPRI Project Manager: J. E. Cummings*

System definition study: phase 1 of individual load center, solar heating and cooling residential project

ER-467-SY Summary Report (RP549-1)

The overall objective of EPRI's residential solar heating and cooling project is to provide the electric power industry with a quantitative basis for evaluating the potential impact of solar and load management systems on utility load factors, revenues, operating costs, and capacity requirements.

This study, performed by Arthur D. Little, Inc., determined preferred concepts for residential solar and load management space conditioning and domestic hot water systems in the northeast and southwest regions of the U.S. Two utility partners were identified by EPRI to represent the regions: Long Island Lighting Co. for the northeast region and Public Service Co. of New Mexico for the southwest region.

The specific objectives of the Phase 1 system definition study were to develop a method for relating the performance of solar and load management heating, cooling, and domestic hot water systems to the service areas of the two utility partners, perform system studies to identify and develop for each service area preliminary designs for five experimental systems, develop an instrumentation and test and evaluation plan for the experiments, and develop plans for the remaining phases of the project. *EPRI Project Manager: J. E. Cummings*

Solar heating and cooling of buildings: requirements definition and impact analysis

ER-475 Interim Report (RP553-1)

The installation of solar heating and cooling of buildings (SHACOB) systems usually requires a backup system—often electric—to take some portion of the load on days of low insolation and to carry the entire load during extended periods of low insolation. The implications of such systems for the economic operation of electric utilities may be significant if a displacement of required generating capacity does not accompany the displacement of revenue resulting from the displacement of energy.

The objective of this study, performed by the Aerospace Corp., is to define SHACOB design concepts that optimize the economic impact for the electric utilities and their customers. In this interim report, the work completed in Phase I of this study is summarized, and Phase II plans are presented.

The emphasis in Phase I has been on establishing a data base and methodology for studying change in utility demand resulting from the penetration of SHACOB systems. Weather and insolation inputs for simulations have been established for locations across the U.S. Reference buildings in nine basic categories have been identified, their thermal properties defined according to ASHRAE 90-75 standards, and detailed internal and external load models generated to characterize building thermal performance. *EPRI Project Manager: J. E. Cummings*

NUCLEAR POWER

Evaluation of temperature coefficients of reactivity for ^{233}U-Th–fueled HTGR lattices

NP-222 Final Report (RP353-1)

The objective of this project by Battelle, Pacific Northwest Laboratory was the development of a calculation capability that can be used for evaluating the response of a high-temperature, gas-cooled reactor (HTGR) to changes in its operating temperature (temperature coefficient of reactivity).

The nuclear data for Th, ^{233}U, and graphite available in the national reference library, ENDF/B-IV, was reviewed. Improved cross-section files for ^{232}Th and graphite were prepared and made available for inclusion in the next version of the ENDF/B library. (The ^{233}U thermal cross sections are being revised as part of another EPRI project, RP707, with the same contractor.) The revised nuclear data were used as a base for transport theory calculations in an attempt to model the behavior of a set of high-temperature lattice experiments carried out earlier at Battelle, Pacific Northwest Laboratory under AEC funding.

These experiments measured variations in the nuclear characteristics (infinite multiplication factors, and so on) of graphite-moderated ^{233}U-Th lattices as they were heated from room temperature to a temperature of 1000°C. Correlations obtained by matching these calculations with measured parameters were then extended to study systems with ^{233}U-Th concentrations typical of those found in commercial HTGRs.

Because of funding limitations, no calculations of actual HTGR systems have been carried out. Such calculations would provide an important test of the validity of this method. *EPRI Project Manager: O. Ozer*

Rewetting and liquid entrainment during reflooding: state of the art

NP-435 Topical Report (RP248-1)

Reflooding is one of the important emergency core cooling mechanisms for LWRs during the hypothetical loss-of-coolant accident (LOCA). This project, which has been under way since 1974 at the University of California at Berkeley, is a part of the continuing theoretical and experimental efforts that have been conducted worldwide in recent years to demonstrate the heat transfer effectiveness of reflooding under simulated LOCA conditions and to enhance the fundamental understanding of the thermal-hydraulic phenomena occurring during reflooding.

This report represents a state-of-the-art review of the physics and the analyses of surface rewetting and droplet entrainment, which govern thermal-hydraulic mechanisms during the reflooding process. Published models of the rewetting process include simple one-dimensional solutions in two axial regions, one-dimensional solutions in three axial regions (with or without percursory cooling), one- and two-dimensional numeric-difference techniques, using temperature-dependent heat transfer coefficients, and analytic two-dimensional solutions. The basic assumptions of these models and the numeric values assigned to the various parameters, as well as empirical rewetting correlations, are discussed. The various mechanisms for liquid droplet entrainment and analytic formulations of the critical gas velocity and of the droplet diameter at the onset of entrainment are reviewed. *EPRI Project Manager: K. H. Sun*

UC-B reflood experimental plan

NP-457 Key Phase Report (RP248-1)

This project, which is under way at the University of California at Berkeley, involves a single-tube reflooding heat transfer facility. The project includes the development of analytic models capable of predicting thermal-hydraulic performance under reflood conditions and a basic experimental program to provide a data base for model development and predictions.

The report provides a detailed description of the concepts and philosophy behind the design and setup of the test facility and of the steam water separator itself. The instrumentation, the selection of the parametric ranges to be investigated experimentally, and the data reduction methods are also discussed. *EPRI Project Manager: K. H. Sun*

In situ response time testing of platinum resistance thermometers

NP-459 Key Phase Report (RP503-3)

Response time has been considered an important property of resistance temperature detectors (RTDs) since their early use for industrial temperature measurement. NRC has since recommended that utilities operating nuclear power plants make in situ time response measurements of sensors installed in the plant.

This key phase report provides interim results of a two-year effort by the University of Tennessee to develop techniques for verifying RTD time response capability in situ. Three methods for verifying RTD response capabilities are described: loop current step response, static self-heating, and noise analysis. Theory, application, and initial experimental results establish the strengths and weaknesses of each method.

Subsequent project work will seek to refine both the self-heating and the loop current step response methods to facilitate plant application by utility personnel. Test instrumentation design and test procedures will be provided along with results from additional in-plant tests at Westinghouse Electric Corp., Babcock & Wilcox Co., and Combustion Engineering, Inc., units. The in-plant data, augmented by laboratory calibrations, should enable ready comparison and confirmation of field test results. *EPRI Project Manager: D. G. Cain*

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