# Energy Forecasting

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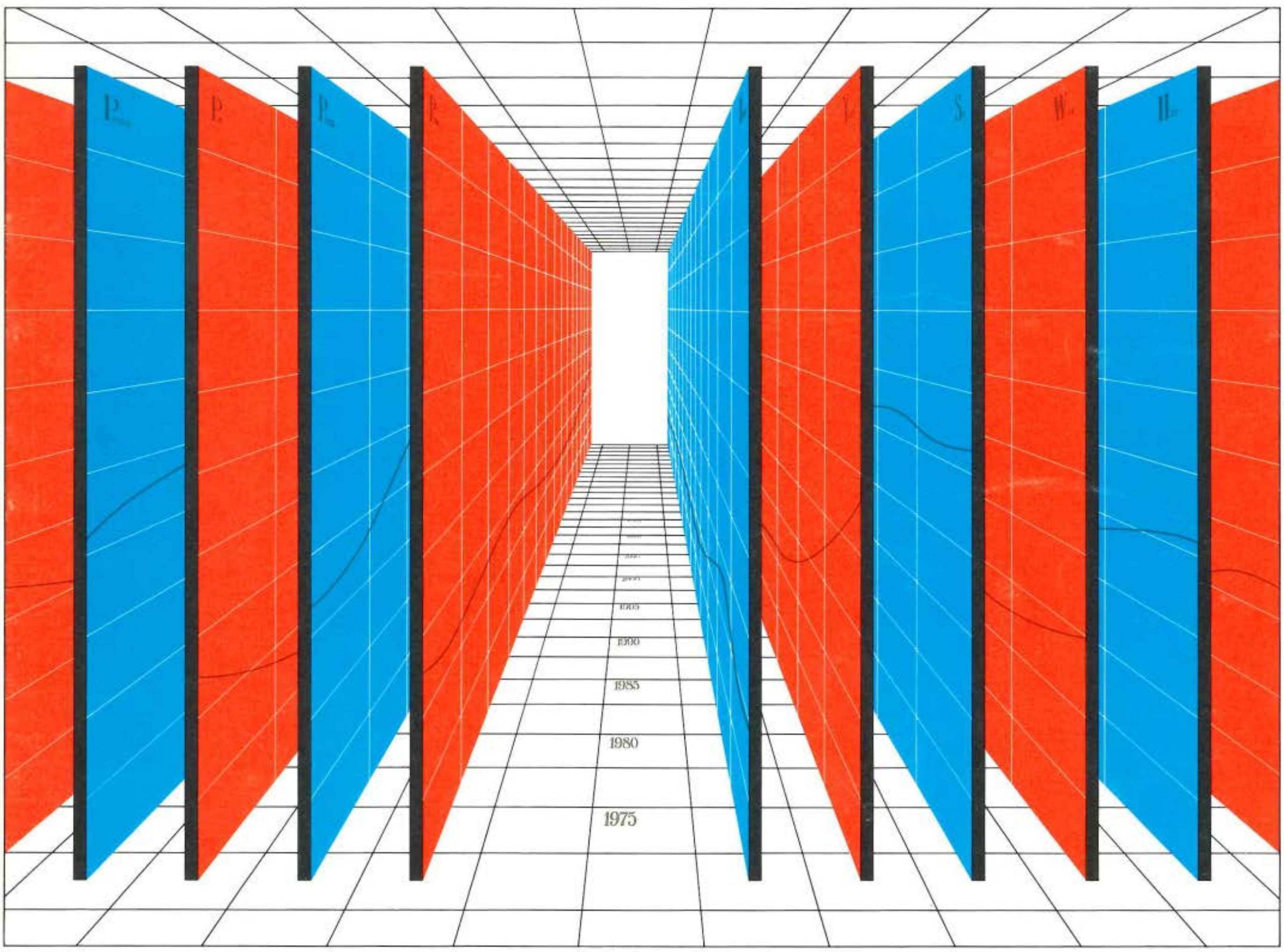

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Cover: The energy path through time is straight, but how wide? Forecasters must define and evaluate many constraints that will influence energy production and use.

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DIVISION REPORTS



DEPARTMENTS

## Models and Residential Demand

The drive to know about tomorrow, before tomorrow arrives, permeates the history of the human race. Whether manifest in religious cultures, in martial or sports endeavors, or in scientific research, the ability to predict the future—even though inaccurately—has been held in high esteem. Whether to the Delphic oracle, to the tipster at the track, or to the market researcher, people have looked for advance information on the outcome of a battle, a horse race, or an election.

For every person who turns to forecasters, knowledge of the future has high value. So it is today with those involved in energy analysis. The course of energy demand over the next few decades will materially affect society and should determine our strategy for developing energy resources, as well as energy hardware.

The art of foretelling the future has advanced since the time when the sniffing of delirium-inducing vapors was the mainstay of prognostication at Delphi. Yet it remains an art, albeit an art firmly resting on the scientific method, honed by the computer-aided ability to digest huge volumes of information.

The pattern of energy growth is multifaceted. In this issue of the JOURNAL the feature article focuses on one of those facets, residential demand. Further, it reviews the use of models—one of the analytic tools of economists—to determine the relationships between residential energy demand and its causal forces. In addition, a report on the Energy Systems Modeling Program reviews the broader applications of modeling and EPRI's plan to evaluate such efforts.

*Modeling* has become a popular and very apt word to describe an analytic process. Simply put, it is the mathematical expression of the essential relationships among physical and human forces. For example, energy modeling is the process of listing the elements giving rise to energy demand and expressing in mathematical terms the way in which they are related. The model is then usually exercised on historic data to validate its mathematical form.

A residential energy demand model must reflect people and their activities. The population expected in the next few decades is fairly well known, but the activities of these people must be conjectured on the basis of past reactions to economic and other stimuli: prices of energy, changes in technology, availability and prices of substitute goods and services (particularly other energy forms), non-price-induced conservation, and household income.

A model is rooted in history, both by the data used to derive the model's coefficients and by the experience of the modeler. It is the analyst-modeler who must nurture it into an accurate image of future activity. This is a difficult task when the future appears to flow continuously from the past. It is fraught with possible error when the future is likely to be discontinuous from the past. In the case of energy modeling, discontinuity appears probable in light of recent abrupt change in energy prices and in attitudes toward energy resources.

Much like the racetrack touts who remember only their winning recommendations, there are modelers claiming value for their entries based on short-term successes. The models we seek are those that will give us the keenest insight into the future. Only experience will reveal their accuracy. In the meantime, careful analysis can help us choose the likely candidates. It is in this spirit that the feature article is written.

René H. Malès, Director
Energy Systems, Environment,
and Conservation Division

# Authors and Articles

Must the JOURNAL's cover feature always review the state of the art in an energy technology? Or are there times when it is equally helpful to explain just what that technology is?

These questions are stimulated by the way EPRI's many projects to develop processes and hardware for energy systems stand in contrast to the demand studies that shape the need for them. For many JOURNAL readers, an easy familiarity marks much of the solar energy and breeder reactor technologies reviewed in the past two issues. Indeed, these terms are even watchwords outside the electric utility industry.

□ But no such widespread understanding could be counted on by James Boyd in writing this month about "Forecasting Energy Use" (page 6). He therefore builds a foundation in econometric forecasting, using the example of the residential sector to do two things: illuminate a vital subject and point out areas of current study that will produce the forecasts EPRI needs to guide its other research.

Boyd earned his undergraduate degree in finance at San Diego State University in 1969. He then turned to economics for his MA (1972) and PhD (1974) at the University of California at Santa Barbara.

While at the university, Boyd lectured in statistics, macroeconomics, and price theory. He also engaged in private consulting on such diverse subjects as auto dealer site selection, water resource allocation, and the economics of criminal behavior.

Since October 1974 Boyd has been a member of EPRI's Energy Demand and Conservation Program, where he manages forecasting studies for the residential sector. His research interests include load forecasting, peak load pricing, economic analysis of regulated industries, and the economics of consumer behavior.

□ "There's a difference between having a good idea, and having it at the right time." Arnold Fickett's words are homespun, but his context is the advanced technology of "Fuel Cells: Versatile Power Generators" (page 14). A 1956 cum laude graduate in chemistry from Bates College, Fickett went straight to General Electric, where he counts himself fortunate in having been assigned to early R&D on fuel cells in 1959.

General Electric established its Direct Energy Conversion Operation two years later, and Fickett became a development engineer on fuel cells for the Gemini program. He was named manager of component development in 1964, of R&D in 1967, and of engineering in 1970—by which time GE's related work had expanded to include water electrolysis, electrochemical gas purifiers, and hydrogen generators.

Between 1961 and 1965 Fickett earned an MS in electrochemistry at Northeastern University. His highly focused aerospace work coincided, and in 1965 he was recognized by *Industrial Research* magazine with an award as co-inventor of the Gemini fuel cell.

Fickett has thus been a part of fuel cell development virtually since its origin. But even though his own and GE's early success was in outer space, the objective always has been to bring fuel cells "down to earth." This brought him to EPRI in April 1974 as project manager for fuel cells in the Electrochemical Energy Conversion and Storage Program. Now, instead of a single company's goals, Fickett has the challenge of helping to focus the efforts of many companies, as well as those of the federal government, on a new kind of power plant that is rapidly moving toward short-term reality.

□ Perhaps the shortest-term reality achieved by any EPRI research to date is reviewed by Tom Fernandez in this month's technical feature, "Pool Swell in a Nuclear Containment Wetwell" (page 20). The task was to develop a qualitative understanding of hydrodynamic forces that might occur in a Mark I containment wetwell. Fernandez and his colleagues worked with Stanford Research Institute to build and operate a scale model that produced initial findings in just 35 calendar days.

The assignment was a natural for Fernandez, whose career interests are fluid mechanics and heat transfer in large energy systems. He had worked in Bureau of Reclamation hydroelectric and pumping plants even before graduating in mechanical engineering from the University of California at Davis in 1965.

Later, working for Shell Oil Co. in secondary recovery techniques for petroleum reservoirs, he was impressed by the effective role of nuclear instrumentation used in well logging. Fernandez therefore returned to school, this time at the university's Berkeley campus, to study nuclear engineering. Specializing in nuclear safety and the thermal performance of reactors, he earned an MS (1968) and a PhD (1971).

For two years thereafter, Fernandez worked in LMFBR safety studies with the Breeder Reactor Department of General Electric Co. He came to EPRI in December 1973 and is now a program manager with principal responsibility for projects in LWR safety.

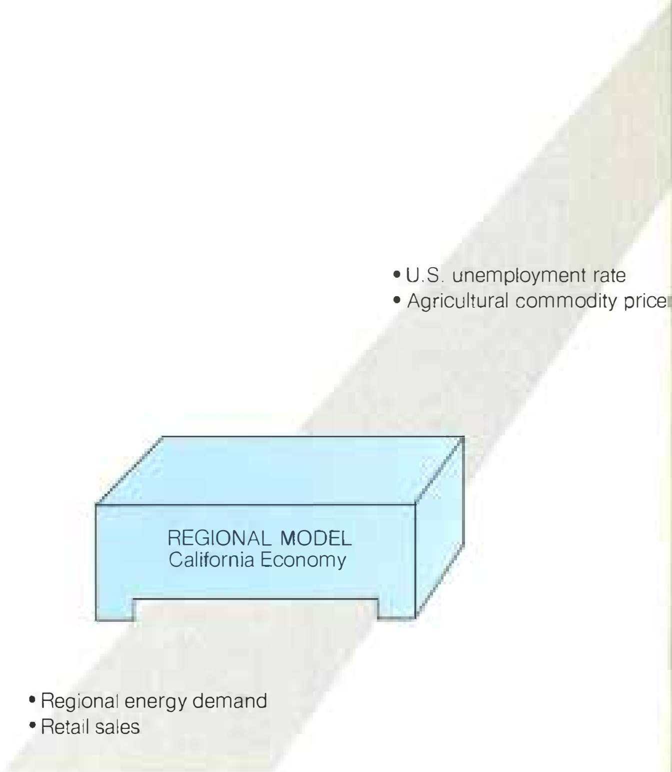

Boyd


Fickett


Fernandez

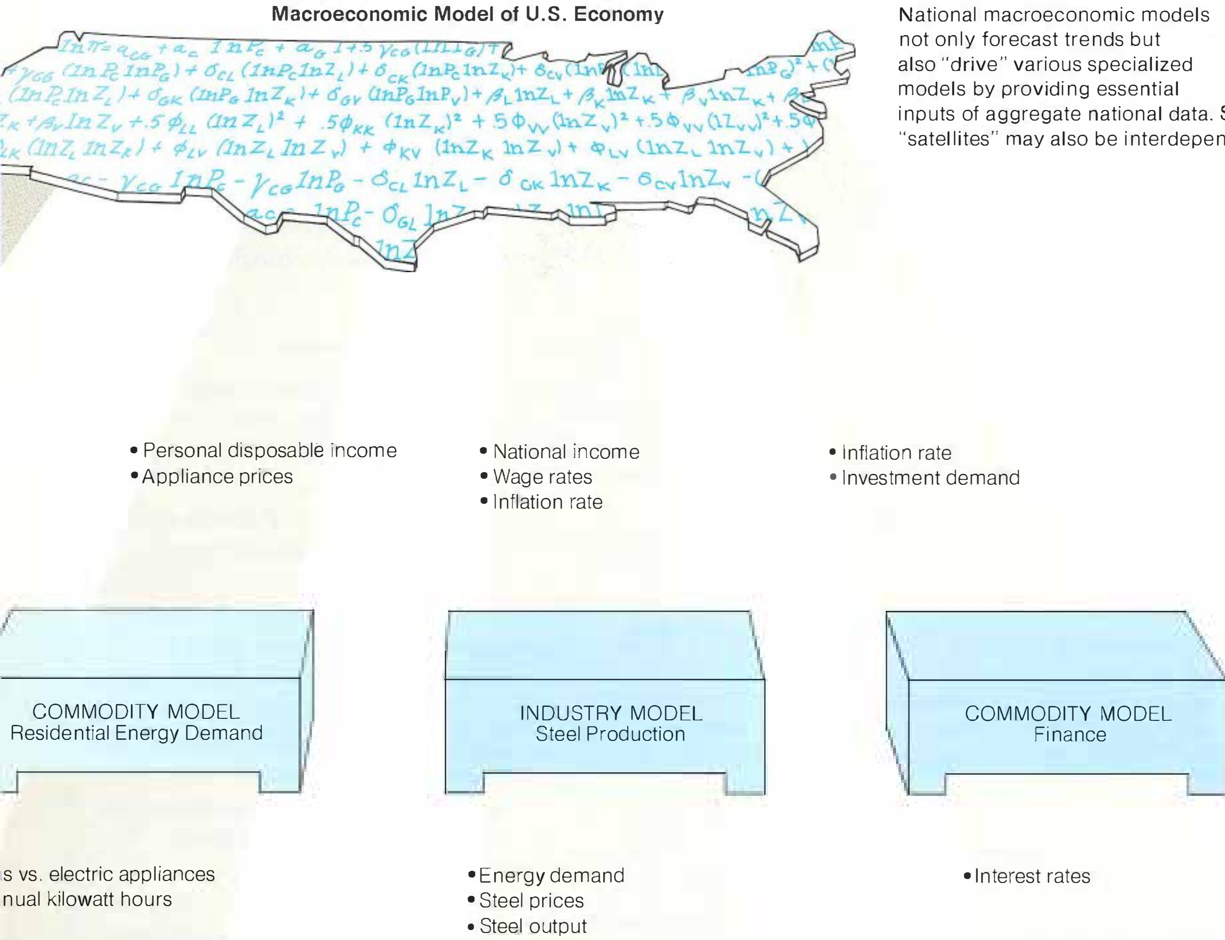
# Forecasting Energy Use: The Residential Sector

James W. Boyd




Mathematical relationships are the economist's forecasting tools. But even when used to model residential energy consumption alone, they involve many variables, many assumptions, and a lot of data for the all-important look into the future. □ An EPRI state-of-the-art feature

James Boyd is a project manager in the Energy Demand and Conservation Program of EPRI's Energy Systems, Environment, and Conservation Division.




National macroeconomic models not only forecast trends but also "drive" various specialized models by providing essential inputs of aggregate national data. Such "satellites" may also be interdependent.

Energy forecasting has brought about a bewildering array of energy consumption models, and it is too often left to the interested but confused reader to analyze their differences and the resulting forecasts. Based on different assumptions of economic growth, energy conservation, and technological change, today's energy forecasts range from zero growth to a rate even faster than has been seen in the past decade. Similarly, electricity growth forecasts cover a broad range.

This article examines a number of forecasting approaches and is intended to assist in understanding and interpreting the various residential energy demand forecasting models in terms of their assumptions and modeling structures. In the process,

**ALLOCATING RESEARCH AND ENERGY RESOURCES**

EPRI's interest in energy demand forecasting is based primarily on the need to set long-term R&D priorities. The focus is on the allocation of research funds among new technological alternatives. Even a partial list includes such diverse possibilities as coal gasification, storage batteries, solar generators, load management devices, and fast breeder reactors.

To deal with its own research allocation problem, EPRI is producing forecasting models. This effort may also provide improved forecasting methods for the planning activities of individual utilities. A further by-product may be better forecasting tools available to the public at large.

Evolving technologies for energy use, rising energy prices, and rising personal income will also critically affect both the need for electricity and the methods of its generation. For example, the relationships among coal, gas, petroleum, and uranium prices will affect the mix of capacity needed to minimize the cost of generating a given amount of electricity. The groundwork for that mix, and for its investment planning, must be formulated now.

Then, too, changing family characteristics, such as fewer children in each family and more women in the labor force, will affect the nature and extent of residential energy demand. Coming to grips with these and other issues in an economic forecasting framework is the topic of this article.

the strengths and weaknesses of these models in alternative forecasting applications are discussed.

The word *demand* in this context is not the common electric utility term for peak demand in kilowatts. Rather, it refers to the economic relationship between a quantity consumed and its determining factors, such as price, user income, and weather.

### Energy consumption growth and timing

The size of the residential sector varies across utility service areas, but households account for about 30% of national electricity use. From 1960 to 1970 residential use grew somewhat faster than overall use, which was growing at about 7% annually. The difference is attributable primarily to an increasing diversity of electric appliances and secondarily to an increasing number of households.

By 1970 residential space heating and air conditioning made up almost 30% of home electricity use. The timing of these uses is naturally determined largely by weather conditions, but it also depends on living routines such as the eight-hour workday. The timing of the remaining 70% is determined mostly by living routines, but it often overlaps weather-related usage during residential peak periods. Similarly, commercial electricity consumption is dominated by heating and cooling uses that are weather-related and/or tied to work hours. By comparison, industrial electricity use is more evenly distributed because of the diverse nature of industrial processes and multiple shift operations. Auto manufacturing, paper, and aluminum industries, for example, generally operate around the clock.

### Wrestling with block rates

Analysis of electricity demand is distinctly different from that of other commodities because of declining-block rate structures for electricity. Lester Taylor, professor of economics at the University of Arizona, discussed some of the residential energy demand forecasting implications of this in a 1975 survey article on the demand for electricity (*1*).

□ Most commodities purchased for household use are marketed at a single price per unit, regardless of the amount purchased. In such cases, economic theory tells us that given the relevant household information about tastes, income, and today's prices, we can generally obtain unique and continuous mathematical expressions describing buying behavior.

□ This is not the case with electricity because its unit price varies according to the amount purchased. With declining-block rate structures, demand may become an erratic relationship among the relevant variables unless the entire rate structure is incorporated into the analysis. The reason is that the consumer always has the option, particularly in the long run, of choosing to buy on a dramatically different block of the rate structure.

□ In standard demand analysis, an infinitesimal change in price produces a corresponding infinitesimal change in the amount demanded. However, a slight decrease in the final (tail block) rate may prompt the consumer to buy significantly more electricity at the lower unit price. He may, for example, decide that an all-electric kitchen has finally become attractive. His decision may produce discontinuous and multivalued demand relationships—something of a nemesis for economics and economic forecasting. Block rates for electricity also complicate the demand for related commodities. The household decision to alter energy demand also changes budget shares and demands for other appliances and for substitute fuels.

To deal with this problem, block-rate structure data were recently collected for EPRI (under RP431) on a national basis and incorporated directly into a forecasting model. This work represents a significant step beyond earlier studies and will improve our forecasting ability as well as our understanding of relationships such as the responsiveness of household energy demand to changing income and prices.

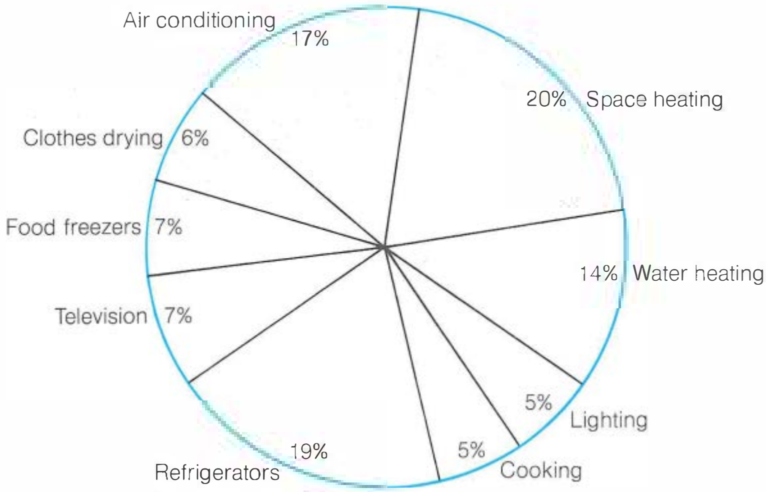
### Models and modeling

We now turn to the problem of matching forecasting models with forecasting objectives. This requires discussing the basic types of forecasting models and their specific relationships to residential energy forecasting.

Most national models are based on aggregate national data. Their objectives are to forecast such variables as national income, inflation, interest rates, and the balance of trade. Well-known macroeconomic models of this type include those of Data Resources, Inc., and Wharton Econometric Forecasting Associates.

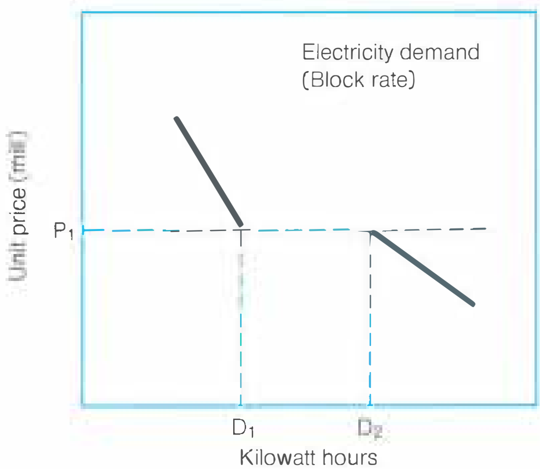
National models are often used to "drive" satellite models by generating needed aggregate input variables. Frequent scopes for satellites include specific industries, end-use commodity classifications, and regions of the country. A typical industry-specific model might concentrate on steel or electric energy producers, whereas an end-use commodity model might concentrate on the household demand for energy or the national demand for natural gas. A typical regional macroeconomic model of, say, the New England area might use forecasts of national models as inputs to produce regional industry and geographic detail not present in national models.

Since the objective of forecasting models is to predict the values of selected independent variables at some future time, an econometric model based on time-series data provides a natural and direct approach. This approach focuses on large numbers of




Source: John Tansil and John C. Moyers. "Residential Demand for Electricity." CONF-730205-2, ORNL-NSF Environmental Program, Oak Ridge National Laboratory.

Not just overall energy growth, but changing patterns of use pose problems for forecasters. As average annual household electricity consumption climbed from 1800 kwh to 7000 kwh between 1950 and 1970, the swing to electric space heat accounted for 20% of the change and the widespread adoption of air conditioning, another 17%. What new patterns will influence the overall change during the next 20 years?




Electricity's block rate structure creates discontinuities in individual household demand curves, making it difficult to forecast consumption. When consumers are motivated to add several appliances, or perhaps an all-electric kitchen, their decisions result in markedly greater electricity consumption, which may qualify them for a lower unit price. To the extent that such shifts in consumption occur, econometricians must incorporate them into their models.

time-related observations, such as annual or quarterly national or state data.

Cross-section analysis, on the other hand, focuses on large numbers of observations at a point in time and often provides a useful though indirect alternative to time-series methods. By examining large numbers of individual households, analysts use cross-section analysis to answer such questions as the impact of income or family size on appliance demand or utilization in the household. Cross-section results are often interpreted as being consistent with long-run equilibrium decisions since the underlying variables are unaffected by time. (A long-run equilibrium decision is a householder's action after having been given sufficient time to change his habits and replace appliances in response to an existing configuration of determining variables.)

**Alternative models**

Three classes of econometric models are useful in forecasting annual residential kilowatt-hour consumption.

*The Autoregressive Model* A number of economists have employed what are known as autoregressive models to forecast annual electricity use. These models use regression analysis to relate a previous value of the variable being explained to its current value, hence the term *autoregressive.* In the case of electricity, we predict the value of kilowatt hours in the next period, using the current value of kilowatt-hour consumption along with other explanatory variables. These models generally forecast annual demand, using relatively few variables.

A number of household behavioral assumptions may be employed by autoregressive models. Common models include the flow adjustment model, the state adjustment model, and what is known as the Koyck lag model. Houthakker, Verleger, and Sheehan (*2*) and Houthakker and Taylor (*3*) have employed flow adjustment models. They assume that actual demand changes from period to period in proportion to the difference between actual demand and desired demand. Desired demand is similar to the equilibrium concept, which refers to what the consumer would purchase if given the time to fully respond to the existing configuration of determining variables. In a sense, the household behavioral assumption is that demand depends on the relationship between what the household wants to consume and what is previously consumed.

The state adjustment model employed by Houthakker and Taylor assumes that energy demand is determined by the household "stock" of appliances, income, and relative prices. The core of this model is a stock variable, which may be interpreted either as a physical inventory or as a psychological quantity in the sense of accumulated habits.

The force-of-habit interpretation applies to electricity because once an appliance is purchased, its use tends to be largely a matter of habit. Many household purchases may be categorized in one of these ways before the actual analysis is performed. This provides the economist with a criterion that the model must satisfy to be meaningful. New car purchases, for example, follow the inventory interpretation, because if we buy this year, we probably will not buy again immediately. Water consumption, on the other hand, obviously involves no household inventory and corresponds more closely to the precepts of habit formation. Most commodities are difficult to classify for all situations and time horizons, but these criteria enable the economist to weed out inapplicable models.

Through a series of algebraic manipulations, the stock variables are removed from the state adjustment model. The final estimation equation is written in terms of the price of electricity, income, and electricity consumption during the preceding period. The usefulness of this approach for electricity demand forecasting is enhanced by the fact that existing appliance stock data are very poor or, in many cases, nonexistent. This increases the appeal of models based theoretically on stocks but not requiring actual stock data for forecasting.

The Koyck lag model provides a third type of autoregressive structure (*4*). The 1973 pooled time-series and the cross-section work by Mount, Chapman, and Tyrell (*5*) applied this type of behavioral assumption to electricity demand forecasting in the commercial, residential, and industrial sectors.

Forecasts of annual electricity use with the Koyck lag model are based on the behavioral assumption that energy consumption is proportional to a geometrically weighted average of previous levels of variables such as income and population. The Koyck transformation allows one to use the above assumptions to derive a simple estimation equation in which future electricity consumption is a function of the last period's consumption and several other independent variables.

While each autoregressive model operates on distinctly different assumptions about household behavior, a number of observations may be made concerning this general class of models. Among them, autoregressive models are attractive because they often involve only a small number of parameters. The presence of the lagged variable tends to make these models forecast reasonably well when compared with alternative simple, single-equation forecasting models. (Readers familiar with the Box-Jenkins time-series analysis (*6*) will recognize the similarity between these models and autoregressive filters.) Also, since the structure of autoregressive models is dynamic, there is no need to assume (and then justify the assumption) that the underlying probability distributions are stationary.

There are also disadvantages in using autoregressive models for forecasting. First, econometricians frequently object to lagged variables since, in application, such models may not test a meaningful household behavioral postulate. Lagged variables too often simply assume that the predicted variable will always behave as it did in the past. To be valid, lagged variables require explicit justification.

A second objection involves basic statistical problems surrounding parameter estimation. Parameter estimates for an autoregressive model will generally be biased from their true values but the models may still forecast well.

*The Appliance Stock Model* Another basic approach to annual electricity forecasting is the appliance stock model. Long-run household energy demand may be viewed as the decision to buy a given stock of appliances and to plan utilization rates for each one. Purchase and utilization decisions both depend on economic variables, such as energy and appliance prices, family income, family size, regional weather conditions, and household expectations for these variables in the future. Once appliances have been purchased, changes in economic variables may tend to alter planned utilization rates and, to some extent, depreciation and expected replacement rates. Following this line of reasoning, several economists have analyzed energy demand in terms of long-run appliance stock and stock utilization decisions, as well as in terms of short-run fluctuations in the utilization rates of fixed appliance stocks. Examples here include Anderson's 1973 study of residential electricity demand (*7*) and the classic work of Fisher and Kaysen (*8*). Appliance stock models often involve no lagged variables and attempt to incorporate relatively large numbers of variables into the analysis. This approach explicitly distinguishes between the household's short- and long-run demands for energy. Short-run demand is determined as the utilization rate of an existing, fixed stock of appliances. Long-run demand for energy is determined by simultaneous decisions concerning appliance stock purchases and stock utilization. These decisions are, in turn, determined by the full set of economic, demographic, and meteorologic factors. In practice, the approach generally involves two stages—individual appliances or appliance groups are first determined, and then their utilization rates (kwh, thermal unit, etc.) are chosen. Appliance stock models are usually specified to include large numbers of variables but accordingly involve additional statistical difficulties in estimation.

One would naturally like to forecast stocks and utilization rates for every appliance in the household, but this is generally not feasible due to data and cost limitations.

There are several approaches to disaggregating the stock of household appliances into sensible categories. Anderson separates appliances that do not have electric energy substitutes available at prevailing prices from those that do. For example, lighting, television, and air conditioning—which do not today have viable fuel alternatives—are separated from heating, cooking, and water heating. The basic reason for this partitioning is that it identifies elasticities and cross-elasticities of demand more precisely than if all appliances were aggregated into a single stock.

A drawback to this approach, however, is that it does not necessarily isolate weather-related uses. Air conditioning and lighting, for example, are often placed in the same group although they clearly have different relationships to weather. This leads one to suggest further partitioning appliance stocks into heating and nonheating uses within the group of commodities that have fuel substitutes at prevailing prices.

Among the appliances that have no fuel substitutes, one might similarly separate air conditioning from non–air conditioning uses. These steps would make it possible to focus directly on the determinants of two of the largest residential uses of electricity, namely, heating and cooling.

*The Aggregate Energy Model* A number of energy researchers have suggested a methodology known as the aggregate energy approach. In surveying a paper by Baxter and Rees on industrial demand for energy (*9*), Lester Taylor briefly summarizes their reasons for rejecting the concept (*1*): "[They] reject the aggregate energy approach because of the requirement to reduce different fuels to a common denominator, which ignores the fact that separate fuels are not all equally efficient converters into final usable energy, and because it ignores the reciprocal relationship between the demand for 'energy' and separate fuels."

Aggregate energy models ignore interfuel substitution possibilities and frequently produce "optimal" solutions that are internally contradictory from the economic standpoint. In spite of the conceptual weaknesses of this approach, its simplicity and superficial logic have caused it to attract an unwarranted amount of attention.

**Time-of-day and seasonal forecasting**

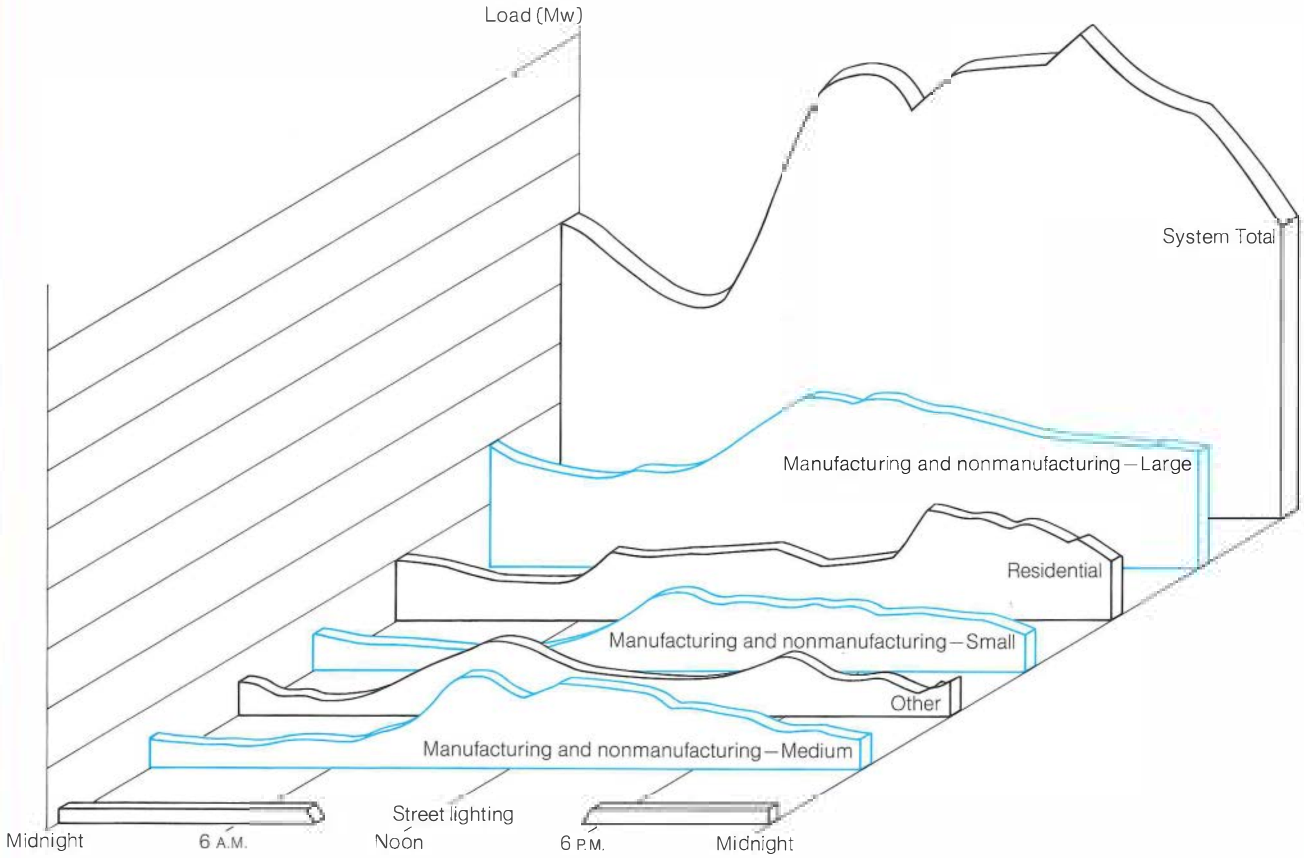
During the past few years, international fossil fuel availability problems have stimulated a great deal of energy modeling research, much of which has been concerned with annual electricity use. Equally important, however, is load (or demand) forecasting by time of day or season of the year. The emphasis on kilowatt-hour forecasting is also attributable to the fact that existing data and long-term forecasting techniques are better suited to this purpose than to dealing with the demand fluctuations inherent in load forecasting. This is particularly true in econometrics.

Annual kilowatt-hour forecasts are

useful for estimating annual fuel requirements for electricity generation and analyzing household interfuel substitution. However, they reveal very little about generation dispatch and capacity expansion needs or the optimal mix of oil, coal, and nuclear generation facilities.

The recent interest in time-of-day pricing for electricity also calls for improved hourly load forecasting. Developing techniques toward this end is essential to organizations such as EPRI that are responsible for determining long-term research and development priorities. The nature of hourly load structures in the year 2000, for example, critically affects the optimal allocation of R&D funds among such alternatives as storage batteries and improved gas turbines for intermediate and peaking power, and coal and nuclear technologies for baseload generation. The first alternative would be supported by the growth of peak demand relative to base demand, while the second alternative would be supported by a relatively level electricity demand profile.

Since load data generally contain a large number of observations, the problem is well suited to time-series analyses




Peak demand is as important to the forecaster as total annual electricity use. Fluctuations within sectors suggest possibilities for load management or rate redesign. They also influence the cost-minimizing mix of generation fuels and equipment, as well as the required capital investment.

such as the Box-Jenkins approach and other more recently developed techniques. Time-series and econometric researchers are therefore examining the possibility of combining these two previously separate approaches to deal with the load forecasting problem (*10*).

#### Problems and directions

A number of current data needs must be satisfied before additional progress can be achieved in the residential sector. Previous data collection activities have often compiled extensive usage data but omitted the economic variables needed for econometric forecasting. Information on population, household income, appliance stocks, and energy prices is essential if we are to utilize existing economic knowledge to relate movements in these variables to energy demand. Evaluating the potential impact of time-of-day pricing on system loads quite naturally requires data on the time of use for residential electricity. Some data currently exist but not in the presence of time-of-day pricing.

Load forecasting and annual kilowatt-hour forecasting will both benefit from the collection of household appliance stock data. Some data are currently available from sources such as the Bureau of the Census, the Bureau of Labor Statistics, and private publications, but they are yet to be combined into a single source capitalizing on the benefits of all available data. These data are important since household energy demand is what economists refer to as a "derived demand" from appliances. To a large extent, the demand for appliances is the long-run demand for household energy.

Finally, a number of economists have noted some fundamental limitations of models based on time-series data in general and existing econometric time-series models in particular. To be properly specified, time-series models must accurately reflect the underlying behavioral lag structure. In the case of household appliances, for example, one must specify the timing and nature of changing appliance stocks in response to higher energy prices. Simple lag assumptions, such as geometric weighting, often fail to capture the true diversity of responses —particularly with aggregate data.

A number of observers have consequently concluded that estimated price and income elasticities are biased downward in aggregate time-series models. These remarks are not so much a castigation of time-series modeling as they are a call for complementary cross-section analysis.

Cross-section data can frequently be stratified into sensible groupings that minimize the loss of theoretical consistency caused by aggregation. This suggests the need for additional cross-section residential energy analysis based on the individual behavioral unit. There exists a small but growing body of economic literature on consistent methods of aggregation that might fruitfully be applied to household appliance acquisition and utilization decisions.

#### Gaps and guidance

Because of national policy interests such as energy independence, much of the early research in residential energy demand forecasting concentrated on annual electricity use aggregated to the state or national level. Most of the studies have been economic-econometric structures, and further development in this area is underway.

Several problem areas remain, such as data limitations, inherent problems with economic models based purely on time-series data, and the inability of models based on overly aggregated data to accurately capture consumer behavior. Future research efforts must fill some of these gaps by concentrating more on household data, specific household appliance groups, time-series load forecasting, and additional cross-section analysis.

Armed with these tools, EPRI and other private and public institutions will be able to produce better forecasts and, hopefully, avoid the potentially huge financial losses associated with incorrect investments in future technologies.

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# Fuel Cells: Versatile Power Generators

Arnold Fickett

First- and second-generation fuel cell R&D is well underway. With a national fuel cell program in the offing, prospects are favorable for multifueled, modular, dispersible power plants to be in commercial use by 1985. ▫ An EPRI program article

Invented in 1839, the fuel cell did not receive its first practical application until over a hundred years later, when hydrogen-oxygen fuel cells provided on-board power for the Gemini and Apollo spacecraft. As a result of space-related fuel cell activities, efforts were initiated in the 1960s to develop fuel cell power plants for terrestrial applications.

The electric utility industry became involved in 1971, when EEI and a group of utilities initiated a fuel cell assessment program with United Technology Corporation (UTC). This program led to FCG-1, an effort sponsored by UTC and nine utilities to place a first-generation, 26-Mw fuel cell power plant in commercial service by 1980. Because of the known limitations of the first-generation power plant, EEI went one step further and established a project to develop a second-generation fuel cell technology (RP114). Aimed at lowering capital costs and improving operational characteristics, the project was intended to expand fuel cell application in the mid- to late-1980s. EPRI assumed responsibility for RP114 in 1973.

### The concept

The fuel cell converts the chemical energy of a fuel directly to dc power without an intermediate combustion or thermal cycle. A single cell produces 0.5–1.0 vdc at a current that is proportional to the cell area. Individual cells are connected in series, as in a lead acid battery, to result in a stack (power section) with an output voltage compatible with the application. This output can be several hundred volts.

In order for a fuel cell power plant to be a useful part of an electric utility system, it must be able to use available fuels and produce ac power. Thus a complete fuel cell power plant includes a fuel processor and a power conditioner. The

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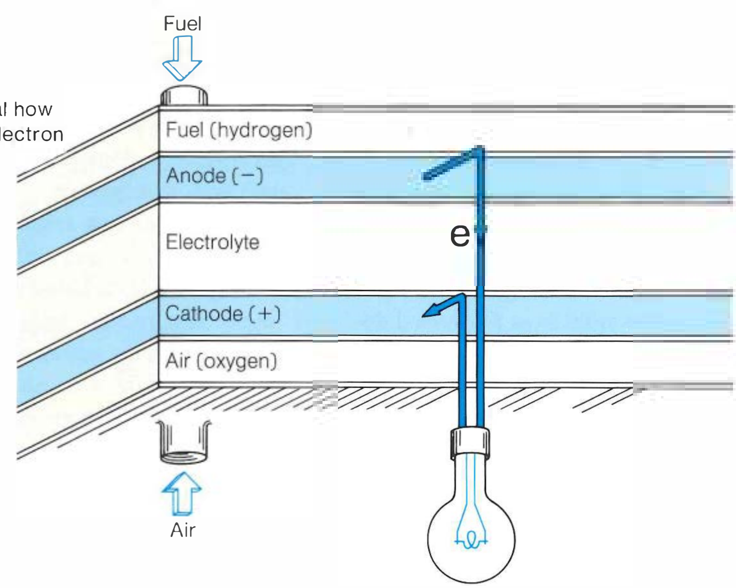
A single fuel cell and a list of its electrochemical reactions reveal how hydrogen and oxygen are combined to produce water and the electron flow that generates dc power in an external circuit.



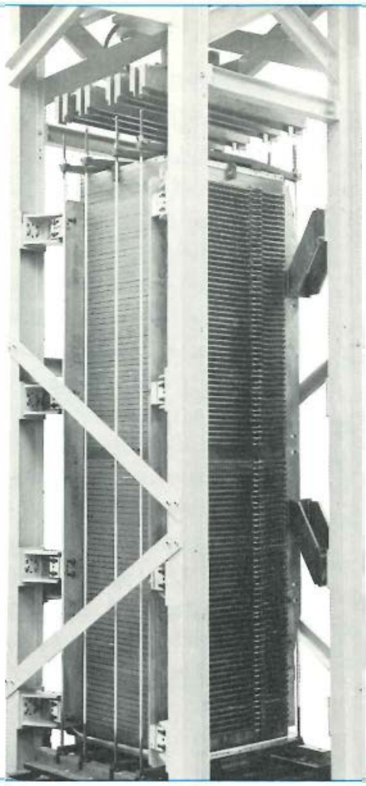

Anode: $H_2 \rightarrow 2H^+_{anode} + 2e_{anode}$

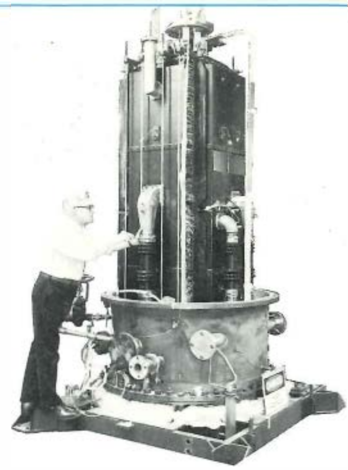
Electrolyte: $2H^+_{anode} \rightarrow 2H^+_{cathode}$

External circuit: $2e_{anode} \rightarrow 2e_{cathode}$

Cathode: $\frac{1}{2}O_2 + 2H^+_{cathode} + 2e_{cathode} \rightarrow H_2O$

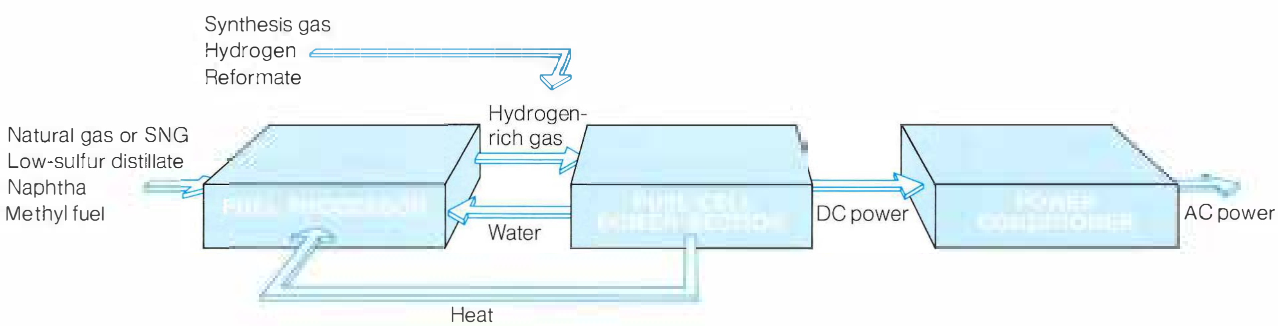
Net reaction: $\frac{1}{2}O_2 + H_2 \rightarrow H_2O$





A stack of 376 phosphoric acid fuel cells was assembled and tested early this year as part of the FCG-1 utility program. About 100 such stacks will be needed for a 26-Mw first-generation power plant. *Photo courtesy United Technologies Corp.*

A complete fuel cell power plant has three functional units. Many fuel alternatives mark the plant's versatility. The fuel processor may be eliminated if synthesis gas or hydrogen—or even reformate—is directly available to the power section.



fuel processor converts a utility fuel to a hydrogen-rich gas and the power conditioner converts dc power to ac power compatible with the utility bus.

### A unique power source

The fuel cell is a unique power generator in several ways:

□ Because it is not a thermal machine, the fuel cell is not limited by the Carnot cycle. It therefore offers the potential for much higher conversion efficiencies than do conventional generators.

□ With modular design, fuel cell efficiency is not related to generator size and small units can operate as efficiently as large ones.

□ Electrochemical devices improve in efficiency as the load decreases, in contrast to conventional generators, which become less efficient at part-load. The fuel cell thus promises superior efficiency when operated in the load-following and spinning reserve modes.

□ Since the fuel cell is not a combustion machine, emissions such as $NO_x$, CO, and hydrocarbons are not a concern. Nor are $SO_x$ emissions a problem because the sulfur content of the fuel stream entering the power plant must be reduced to attain long life. Such low emission levels, coupled with the fuel cell's quiet, water-conserving operation, result in environmental acceptability.

Given these characteristics not presently available in conventional machines, the fuel cell could perform several beneficial functions within utility networks (Table 1). Its versatility opens up a range of potential applications and divergent possibilities for the direction of EPRI's fuel cell program. For example:

□ *Should we concentrate on a dispersed fuel cell to operate on petroleum?* Such a power plant would become important to utilities in the near term while conserving fossil fuel resources.

□ *Should we divert our limited resources to develop a central station coal-consuming fuel cell power plant at 50% overall efficiency?* The promise of these high efficiencies is extremely tempting, although the concept is high risk and longer range.

**Table 1**
**FUEL CELL ROLES IN A UTILITY SYSTEM**

| Role | Possible Users | Benefits |
|---|---|---|
| Dispersed generator, 25–50 Mw capacity | Environmentally constrained utilities | Deferred T&D |
| | | 7500–9300-Btu heat rate |
| | | Improved load-following characteristics |
| | | 2-year lead time |
| | | Incremental growth to match demand |
| | | Reduced transmission losses |
| | | ≤4% forced outage |
| Dispersed generator, 5–25 Mw capacity | Municipal and rural cooperatives | Independent power generation, plus all the above benefits |
| Integrated coal gasifier–fuel cell central station, ~400 Mw capacity | Coal-based utilities | 7500–7800-Btu heat rate (coal to ac power) |

### EPRI program thrust

The EPRI fuel cell program is now focused on developing a second-generation fuel cell power plant with the characteristics described in Table 2. This dispersible fuel cell plant would consume low-sulfur distillate, as well as clean-coal-derived liquids and gases. Such a power plant could save the utility industry \$10–\$20 billion in production costs between 1985 and 2000. It would provide a dispersed option for environmentally constrained private and government utilities, as well as for municipal and rural cooperatives.

EPRI will also assess the impact of an integrated coal gasifier–fuel cell power plant. The fuel cell technologies considered will be compatible with both the dispersed and the central station coal gasifier–fuel cell concepts. At present, however, there are no plans to take the coal concept beyond the assessment phase.

Since it focuses on second-generation technology, the EPRI program has to be predicated on a logical sequence of events. As with any emerging technology, there is an associated set of "critical issues" that will determine whether the fuel cell can penetrate the commercial market. Some of the issues are technical and can be addressed, and to an extent controlled, by program direction. Other issues are institutional and much more difficult to project or control. For the second-generation fuel cell these issues include: emergence of a national fuel cell program, successful commercialization of FCG-1, the types of fuels available, potential applications of fuel cells in utility systems, and the proven economic feasibility of fuel cell technology.

### National fuel cell program?

In 1974 and 1975, despite a major commitment by the utility industry, there was no support of fuel cell development by the federal sector. The preliminary 1976 ERDA budget reflected only token support. Therefore, providing assistance to

**Table 2**

**SECOND-GENERATION FUEL CELL POWER PLANT**

| *Characteristic* | *Goal* |
|---|---|
| Installed cost ($/kw) | $200 (1975 dollars) |
| Heat rate—HHV (Btu/kwh) | |
| Full load | 7500 |
| 20% load | 7300 |
| Lifetime (hr) | |
| Power plant | 160,000 |
| Fuel cell stack refurbishing | 40,000 |
| Fuel capability | Low-sulfur distillate<br>Clean-coal-derived fuels<br>Synthesis gas<br>SNG<br>Methyl fuel |
| Modular size (Mw) | 5–10 |
| Water requirements | None |
| Exhaust emissions (lb/$10^6$ Btu) | |
| $SO_x$ | $\leq 10^{-4}$ |
| $NO_x$ | $\leq 2 \times 10^{-2}$ |
| Noise level @ 100 feet (dB) | ≤50 |
| Operating and maintenance cost (includes stack refurbishing) | |
| Variable (mill/kwh) | 2.5 |
| Fixed ($/kw yr) | 0.3 |
| COMMERCIAL INTRODUCTION | 1985 |

**Table 3**

**ECONOMIC COMPARISON OF FUEL SUPPLY OPTIONS IN 1985[1]**

(1975 dollars)

| *Option* | *Fuel-Cell Fuel* | *Fuel Cost[2] ($/$10^6$ Btu)* | *Fuel-Cell Heat Rate[3] (Btu/kwh)* | *System Capital Cost[4] ($/kw)* | *Figure of Merit[5]* |
|---|---|---|---|---|---|
| Dispersed fuel cell using distributed petroleum product | Low-sulfur distillate | 2.49 | 7500 | 205 | 30.3 |
| | Naphtha | 2.59 | 7500 | 205 | 31.0 |
| Dispersed fuel cell using distributed coal-derived fuel | Synthesis gas | 4.38 | 8200 | 145 | 44.1 |
| | SNG | 3.98 | 7500 | 205 | 41.4 |
| | Hydrogen | 5.84 | 6500 | 180 | 48.2 |
| | Methyl fuel | 4.70 | 6500 | 235 | 41.9 |
| Central station coal gasifier–fuel cell power plant | Coal | 1.47 | ~7800 | ~400 | ~24.0 |

1. Data abstracted from EPRI 318, *Assessment of Fuels for Power Generation by Electric Utility Fuel Cells*, Final Report, prepared by Arthur D. Little, Inc., October 1975.
2. Delivered to fuel cell power plant.
3. Fuel-cell fuel to ac power.
4. Conversion of fuel-cell fuel to ac power (not including interest during construction or installation).
5. Lower values are more favorable.

the federal sector in the formulation of a national fuel cell program became a major endeavor. In part because of EPRI's efforts last year, ERDA has now initiated a dynamic fuel cell activity that is likely to expand to a national fuel cell program.

Such a program would provide an umbrella under which fuel cell developments by EPRI, ERDA, DoD, and others could be coordinated. Although EPRI's work is structured to be essentially self-sufficient through a complementary cycle of development and verification, a national program would do much to assure commercialization of results. It would also reduce the risk by broadening the scope of research activity related to fuel cells.

### Success of FCG-1

A second-generation fuel cell implies the existence of a first-generation power plant. EPRI's goals have little meaning if the FCG-1 power plant is not successfully commercialized.

Individual utilities have supported FCG-1 since 1972. In 1976, in order to expedite commercialization, EPRI undertook an active role. EPRI, ERDA, and UTC are now planning a 4.8-Mw demonstration project to fabricate and test on a utility system a complete module of a 26-Mw FCG-1 power plant. This demonstration is planned for 1978.

### Fuel cost and availability

In late 1974 EPRI contracted with Arthur D. Little, Inc., to assess optimal approaches for integrating fuel cells within a utility fuel supply system (RP318). The study considered raw fuel cost and availability, fuel processing, fuel transportation and storage, and fuel processor integration with the fuel cell power section. Representative data resulting from this assessment appear in Table 3. These findings indicate that:

- Oil-based utilities should consider low-sulfur distillate fuel for use with dispersed fuel cells prior to 1985, and second-generation development programs should focus on the steam reformation of distillate fuel.

□ Readily stored and transported clean-coal fuels (such as SNG or methyl fuel) will not be significant factors to electric utilities until after 1990.

□ Coal-based utilities should assess an integrated coal gasifier–fuel cell power plant as a baseload central station generator operating at 45% overall efficiency (coal to ac power).

### Utility system application

In November 1975, after the fuel assessment study was completed, Public Service Electric and Gas Co. of New Jersey was asked to assess fuel cell roles in utility systems. This project (RP729) will compare the technoeconomics of fuel cell power plants with those of conventional generators by carrying out a 20-year expansion of a reference system and determining production cost savings made possible by using dispersed fuel cells with the characteristics listed in Table 2. The project will also attempt to define capital cost versus market penetration, the benefits of using fuel cells for load-following and as spinning reserve, the benefit of modularity, and the value of dispersed generation. In effect, this project will put on a firmer basis the quantitative goals of the EPRI fuel cell program. In addition, it will assist developers in defining the ultimate market potential based on fuel cell economics and operating characteristics.

### Technology goals

In order for a fuel cell to be economically feasible, it must operate for 40,000 hours at 0.8 vdc (consistent with a 7500-Btu heat rate) and at a power density consistent with $200/kw capital cost.

These goals apply to all three of the fuel cell technologies being considered within the context of the EPRI program: phosphoric acid, at 160–200°C; molten carbonate, at 600–750°C; and alkaline, at 100–150°C. While there are other fuel cell technologies that show long-range potential, it is unlikely that any could be commercial by 1985.

In the jargon of fuel cell R&D, technologies are defined by the electrolyte (phosphoric acid, molten carbonate, or alkaline) and by the operating temperature. These simple designations connote many other system and component characteristics to the fuel cell technologist.

Phosphoric acid at 160–200°C (used in the FCG-1 fuel cell) defines a system that is primarily limited by electrocatalyst performance and life. Except for small amounts of noble metal catalysts, carbon is the exclusive building material for the electron-conducting components. Because acids are able to reject carbon dioxide, this technology integrates easily with fuel streams containing carbon dioxide and small amounts of carbon monoxide. In order for phosphoric acid technology to meet EPRI program goals, a breakthrough in the electrochemical performance of the air cathode is necessary. Therefore, supporting technology programs are focused on air cathode performance.

A molten carbonate fuel cell operating at 600–750°C does not require noble metal catalysts. The required electrochemical performance appears to be achievable based on a reasonable extrapolation of the state of the art. Nickel is used extensively in the current-collecting components. Since the molten carbonate fuel cell involves carbon dioxide in the electrochemical reactions, fuel streams containing carbon dioxide, as well as large amounts of carbon monoxide, are easily integrated. The integration of a molten carbonate fuel cell with a coal gasifier is of particular interest because of the cell's compatibility with coal gas. Improved stability of the materials and verification of a 40,000-hour capability in full-scale, multicell stacks are near-term objectives of molten carbonate studies.

The alkaline fuel cell operating at 100–150°C represents a low-cost configuration, with good electrochemical performance and the potential for long life. Nickel and stainless steel can be used as the metallic components. The major problem is that carbon dioxide reacts with the electrolyte, interfering with performance. Thus the carbon dioxide has to be removed on a continuing basis from the fuel and air or from the electrolyte. Development of efficient, low-cost technology for carbon dioxide removal has become the focus of alkaline fuel cell projects.

Fuel cell technology goals are being carefully addressed in EPRI program planning. RP114 is concerned with phosphoric acid and molten carbonate technology, and RP584 with Exxon Enterprises will evaluate the potential of the Alsthom-Exxon alkaline fuel cell technology.

Supporting these major activities are:

□ A phosphoric acid cathode catalyst effort with Case Western Reserve University

□ A phosphoric acid catalyst sintering investigation with Exxon Research and Engineering

□ A molten carbonate catalyst sintering investigation with Northwestern University

□ A carbon dioxide separation assessment with Giner, Inc.

The present EPRI plan calls for pursuing all three fuel cell technologies through 1978. The most promising technology would then be funded through testing a multikilowatt fuel cell unit.

### Prognosis

Based on the orderly and favorable progress of recent years, it is both tempting and logical to consider what the future holds for fuel cells. For the five critical issues we have discussed, a reasonable prognosis is:

□ ERDA's present fuel cell activity will expand into a national fuel cell program during 1976.

□ A successful 4.8-Mw demonstration of the FCG-1 technology, jointly sponsored by EPRI and ERDA, will be completed by 1979. The FCG-1 power plant will subsequently achieve commercial status between 1980 and 1982.

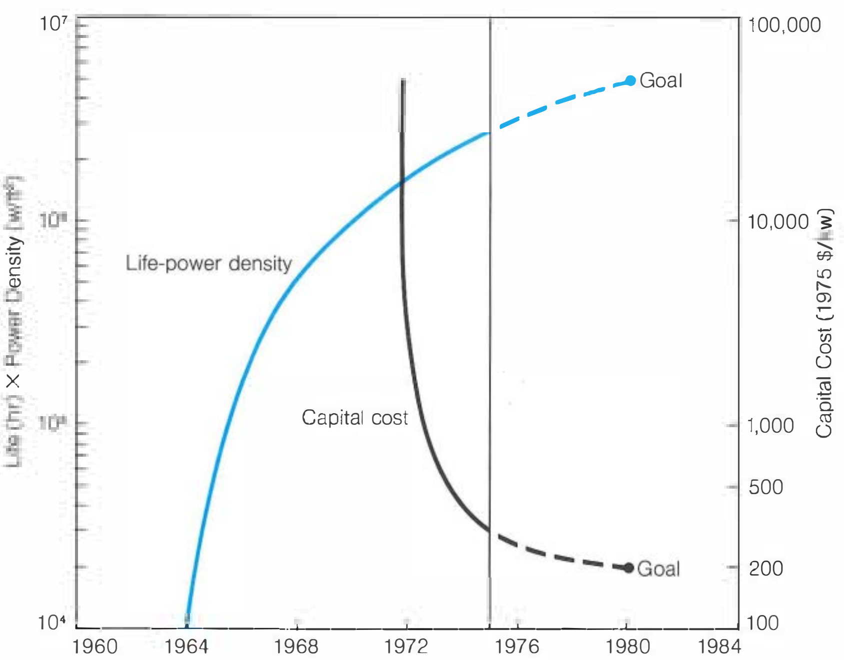
## EARLY SUCCESS ENCOURAGES OPTIMISM

Two useful observations about fuel cells are offered by Peter Lewis, assistant manager of research and development for Public Service Electric and Gas Co. in New Jersey. His company joined TARGET (Team to Advance Research for Gas Energy Transformation), a consortium formed in 1967 by United Technology Corporation and a group of gas utilities. Lewis says of that experience:

"PSE&G installed three fuel cell power plants at its City Dock substation during 1972. These plants used both gas and liquid fuels. Their operation was very successful, meeting all design objectives and providing a degree of reliability in electricity supply that has not been demonstrated with conventional generating equipment. Since 1973 we have been operating a modified TARGET fuel cell in our Energy Laboratory as part of a hydrogen energy storage experiment. This installation demonstrates the flexibility of fuel cell power plants in operating with other fuels."

Today Peter Lewis is also chairman of the Fuel Cells and Hydrogen Working Group, part of EPRI's industry advisory structure. In that role he looks ahead:

"As the nation turns to nuclear power and coal to supply electric energy, there is a need for new types of generating equipment that can use fuels derived from these sources to complement the economics of baseload generation. The fuel cell power plant—with its environmental attractiveness, its high efficiency that improves at part-load, its fast response to changes in demand, and its modular design that shortens construction lead time—has excellent prospects for meeting these requirements. Additional development of fuel cells on a large scale is warranted to determine if satisfactory capital cost and life-expectancy characteristics can be achieved."




Favorable progress in fuel cell research over the past 10 years suggests that EPRI's program goals will be demonstrated by 1980: 125-w/ft² power density, 40,000-hr life, and $200/kw capital cost. Allowing 5 years thereafter for commercial development, second-generation fuel cell power plants could be operating on utility systems by 1985.

□ The U.S. fuel situation will remain vague, forcing fuel cell development programs to remain flexible in the consideration of fuels. The integrated coal gasifier–fuel cell concept will be of increased interest to both EPRI and ERDA.

□ Utility application analyses will indicate that a fuel cell with the characteristics specified in Table 2 can penetrate a large fraction of the power generator market, especially if the price of fuels (coal, petroleum, and uranium) continues to rise. In fact, it is possible that the capital cost requirement could be relaxed without significantly reducing the market penetration of fuel cell power plants.

□ The major issue—and the one we can influence most—will become the development of a technology consistent with the goals for a second-generation fuel cell power plant. Based on past experience, the likelihood of success can be estimated, as shown in the graph. Assuming that five years are required to commercialize a demonstrated technology, our technological goals must be reached before 1980 if commercial introduction is to be possible by 1985.

### Ultimate fuel cell roles

Individual electric utilities will have to determine the ways in which they can best utilize the unique characteristics of the fuel cell. Should it be used with coal or oil? For peaking or for spinning reserve? At a central station or dispersed? EPRI today knows only of the fuel cell roles seen by relatively few cooperating utilities; our second-generation program reflects primarily their perceptions.

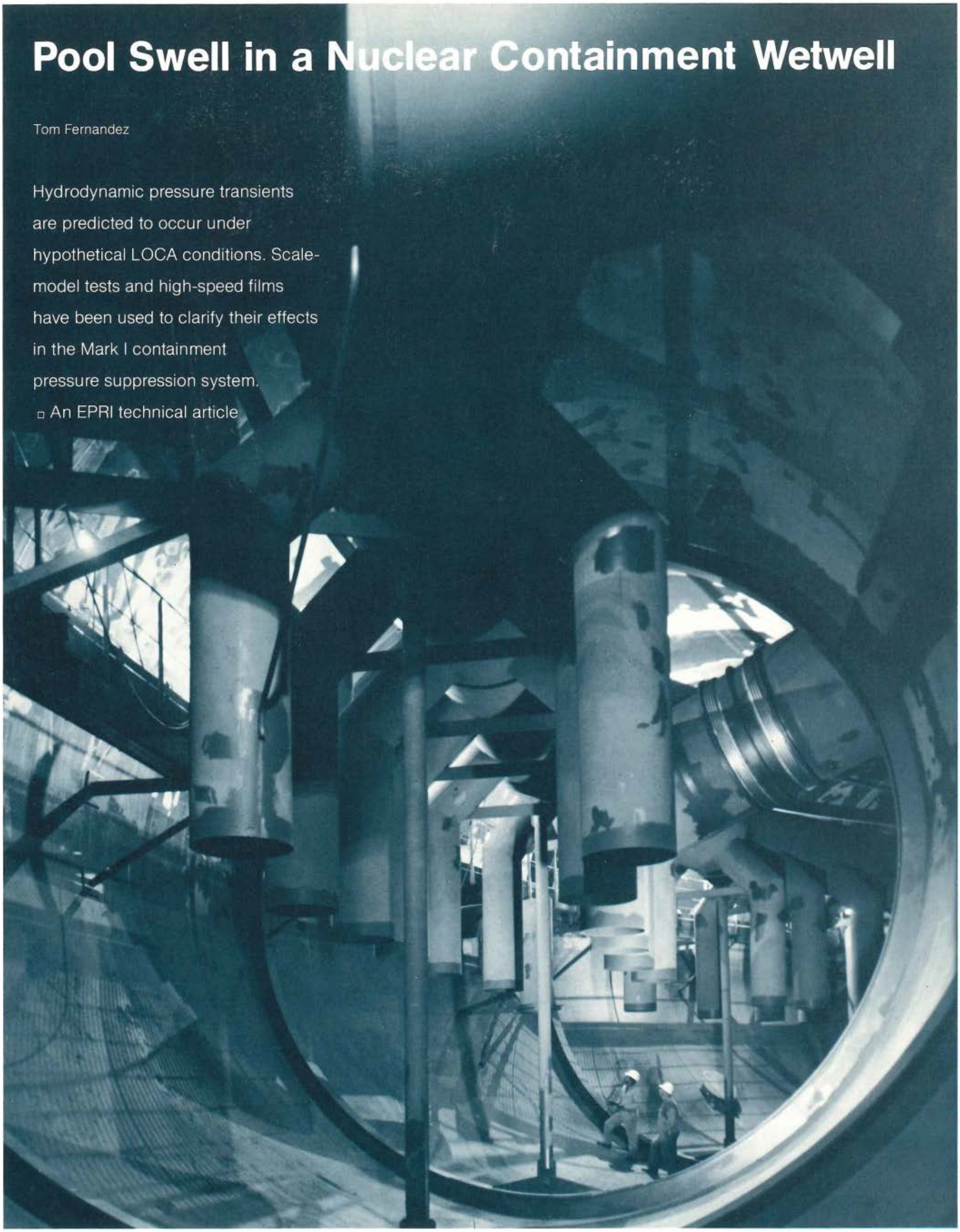
This is not enough. As we continue along a distinctly encouraging technological path, the program will benefit from the identification of additional utility requirements that might be met by fuel cells, with attendant benefits for the power system. EPRI therefore encourages inputs from still more utilities to assist in defining specific optimal roles for fuel cell power plants.

# Pool Swell in a Nuclear Containment Wetwell

Tom Fernandez

Hydrodynamic pressure transients are predicted to occur under hypothetical LOCA conditions. Scale-model tests and high-speed films have been used to clarify their effects in the Mark I containment pressure suppression system.

□ An EPRI technical article



What hydraulic events are expected to occur in a containment pressure suppression system under postulated loss-of-coolant accident (LOCA) conditions? What hydrodynamic forces are the result? The answers to these questions include a momentary swelling of the wetwell water surface when drywell gases are vented, and the subsequent impact of the water on structures in the wetwell.

Identified in the course of nuclear reactor containment design activities, pool swell was recently a subject of scale-model investigation to determine its effects in earlier Mark I systems. The assessment was undertaken by the Mark I Containment BWR Owners' Group, comprising 15 utilities that own and operate 18 boiling water reactors (BWRs) with a total installed gross capacity of 14,500 Mw.

The question before the Owners' Group—and the Nuclear Regulatory Commission (NRC)—was the dynamic response of the Mark I pressure suppression system and its capability to withstand hydrodynamic loads in event of a hypothetical LOCA. The Owners' Group contracted with General Electric Co. to assess this and other generic issues of Mark I containment performance. Additional support was provided by Bechtel Corp., MPR Associates, Inc., Nutech, Inc., Teledyne Materials Research, and, beginning in June 1975, EPRI.

A major part of the subsequent EPRI effort involved sponsorship of $\frac{1}{10}$-scale-model tests. Their objective was to obtain, within a time frame of one month, a qualitative understanding of wetwell pool response during the very early phase (less than 1 sec) of a simulated LOCA. If obtainable, quantitative data were also desired.

Conceived by the Safety and Analysis Department of EPRI's Nuclear Power Division, the tests were performed by Stanford Research Institute (SRI). The model was designed, assembled, instrumented, and tested within three weeks. Test results, including high-speed films of seven tests, were presented to the Owners' Group, other support organizations, and NRC in July 1975.

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This article briefly reviews the Mark I containment configuration, the model design, the conduct of tests, and the findings that helped clarify the nature and effects of pool swell in Mark I pressure suppression systems.

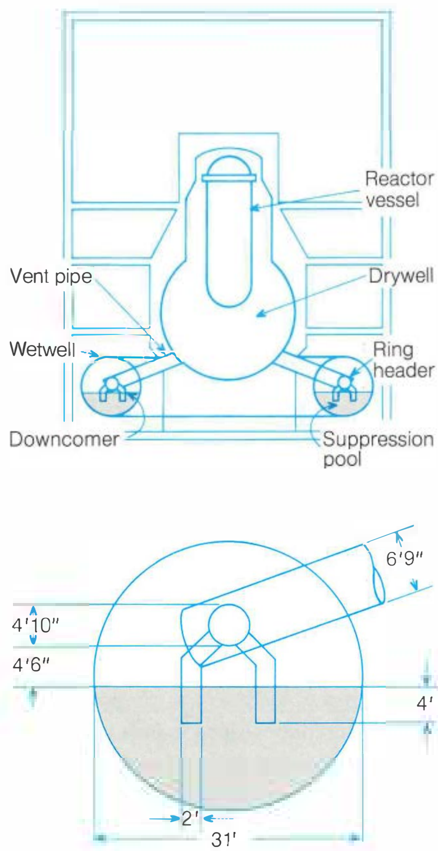



Figure 1 Toroidal wetwell is designed to receive drywell discharge through radial array of vent pipes. Detail shows configuration and dimensions of venting components in the wetwell.

### Containment configuration

As with other BWRs, the Mark I containment features a drywell surrounding the reactor vessel. Primary coolant pipes are in the drywell. Major elements of the pressure suppression system (Figure 1) are radial vent pipes, a ring header in the torus (wetwell), and a number of downcomer pipes (usually in pairs). Together, they are capable of quickly delivering a large volume of gas from the drywell into the wetwell. Under normal conditions, the wetwell is approximately half full of water, and the downcomers extend about 4 ft beneath the surface of the suppression pool.

Even more than Figure 1, the photograph suggests the enormous size of the wetwell in a representative Mark I system. It has an azimuthal diameter (at centerline) of 110 ft and typically contains about 48 pairs of downcomers coming off the ring header. These dimensions were used for the initial generic investigations; however, Mark I containment designs vary from plant to plant.

### Hydrodynamic response

Critical phenomena in the wetwell pool are best described by the scenario of events anticipated within the first second following a LOCA in the drywell. Immediately after the postulated pipe break, primary system coolant (at about 1000 psig) discharges into the drywell, causing its pressure to rise. This, in turn, causes the air in the vent pipes, ring header, and downcomers to be discharged into the suppression pool. Drywell gas follows the initial air discharged into the pool. This gaseous discharge causes the pool surface to rise, strike, and eventually flow past the upper structures, such as the ring header and vent pipes. At the same time, the ambient air above the pool compresses and tends to oppose the pool swell.

Because of the several interacting fluid regions and their moving boundary conditions, the exact hydrodynamic response of the suppression pool is not easily calculated. In early investigation for the Mark I Owners' Group, one of the primary loads appeared to be an upward hydraulic impact against the ring header. The cross-sectional shape of the pool surface and its velocity at the time of this impact therefore became EPRI's particular concern in the model studies. A primary reference tool was available from General Electric's analysis: predicted drywell and wetwell transient pressures (Figure 2) for the plant geometry described earlier. These pressure "histories" were used as a guide in scoping the model tests.

### Model design

Because of the short time available, the model studies were aimed mainly at obtaining qualitative data. Strong emphasis was placed on a high-speed photographic record. Time also dictated simplicity of the model so that several test runs might be completed and evaluated.

A model of the entire toroidal pressure suppression system was out of the question for reasons of both time and cost; also, it would have made visual observation difficult. Therefore, a unit cell was designed—a segment of the torus with one pair of downcomers—to provide a clear view of pool-swell dynamics. Figure 2 shows the completed $\frac{1}{10}$-scale model constructed of clear plastic with flat, parallel end plates.

Since the calculated average spacing of downcomer pairs along the ring header in the reference system is 7.2 ft, the length of the model cell is 0.72 ft and its diameter is 3.1 ft. Essentially all other dimensions were similarly scaled down by a factor of 10. However, the ring header in the reference system supplies flow to several pairs of downcomers. Because the model has only one pair, its vent pipe and ring header flow passages had to be specially scaled to produce an equivalent flow resistance. A shroud was then mounted around the ring header segment to restore the correct scale of its outer diameter.

### Pressure scaling

As described above, ambient air in a Mark I wetwell compresses slightly during the early period of interest (Figure 2, wetwell curve), tending to oppose the pool swell. In the plastic model cell, however, such pressures were not possible, and a port was cut in the top of the cell to vent air from the cell during tests. The desired prototypical hydraulic performance was preserved by modifying the drywell pressure history as follows:

A scaled drywell pressure history for the test system was determined by scaling the difference between the drywell and wetwell pressure histories shown in Figure 2. Scaling analyses indicated that the magnitude of the transient pressure difference should be multiplied by the geometric scale factor (0.1) and that the corresponding elapsed time should be multiplied by the square root of the geometric scale factor ($\sqrt{0.1}$).

To simulate a drywell, an empty air tank was connected to the ring header of the model. This tank, in turn, was fed from a pressurized air tank. The connection between the two tanks was fitted with a quick-acting valve, a throttling valve, and a burst diaphragm. Together, these were used to control the pressure transient in the drywell simulator tank.

### Conduct of tests

Seven tests were performed, with scaled drywell pressure histories below, near, and above the reference pressure history for the model. Figure 2 shows the measured drywell pressure histories and the reference history for the tests. Note that the traces for tests 1, 3, 2, 6, and 4 (in ascending order on the graph) bracket the reference trace. Also note that tests 5 and 7 provide near replications of Test 3 and of the reference trace, particularly during the period of interest, the first 0.2 sec. These three tests were photographed from different positions in order to obtain different views of the pool-swell process.

The films are the most important results of the model test effort. Taken at a nominal speed of 1000 frames/sec, the films provide a detailed record of the phenomena likely to occur in a Mark I suppression pool during the very early phase of a postulated LOCA. Films from the various tests show similar features, although the timing of events varies somewhat. Figure 3, a sequence of frames from Test 2, clearly illustrates the pool swell.

### Observations

As the drywell pressure begins to rise, water is displaced from the downcomers. Essentially no kinematic effects are per-

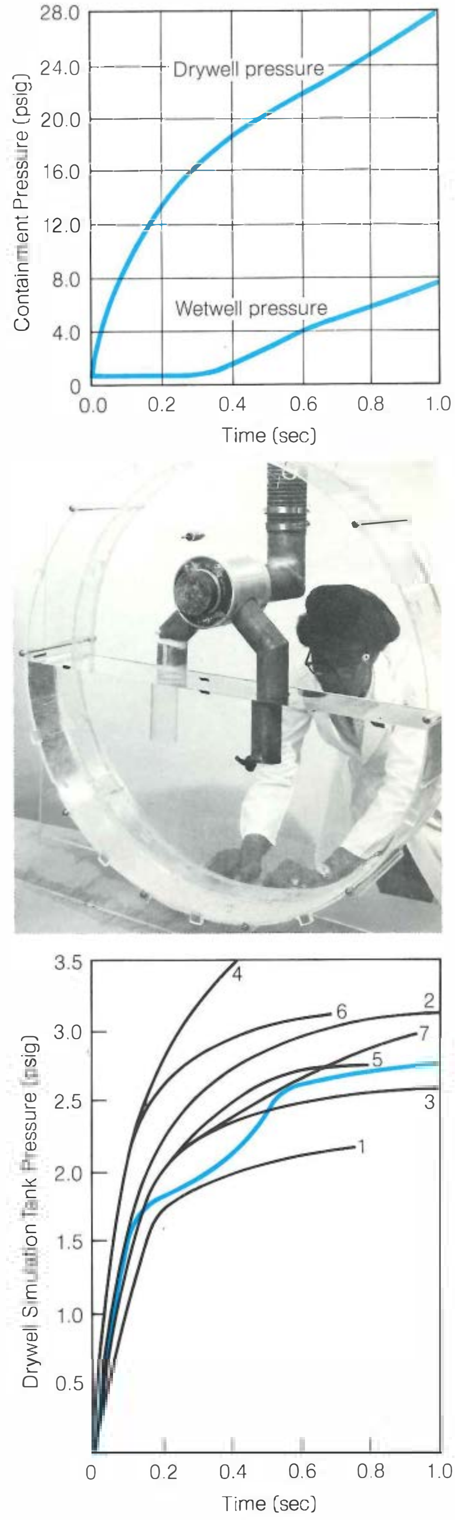



Figure 2 Pressure phenomena within the first second after a LOCA in the drywell are reflected in predicted pressure-time histories for a full-size Mark I drywell and wetwell (top). The drywell history was scaled down for tests in SRI's plastic model of a torus segment (center), producing the reference pressure history (bottom). Seven tests were designed to bracket the reference trace, shown in color.

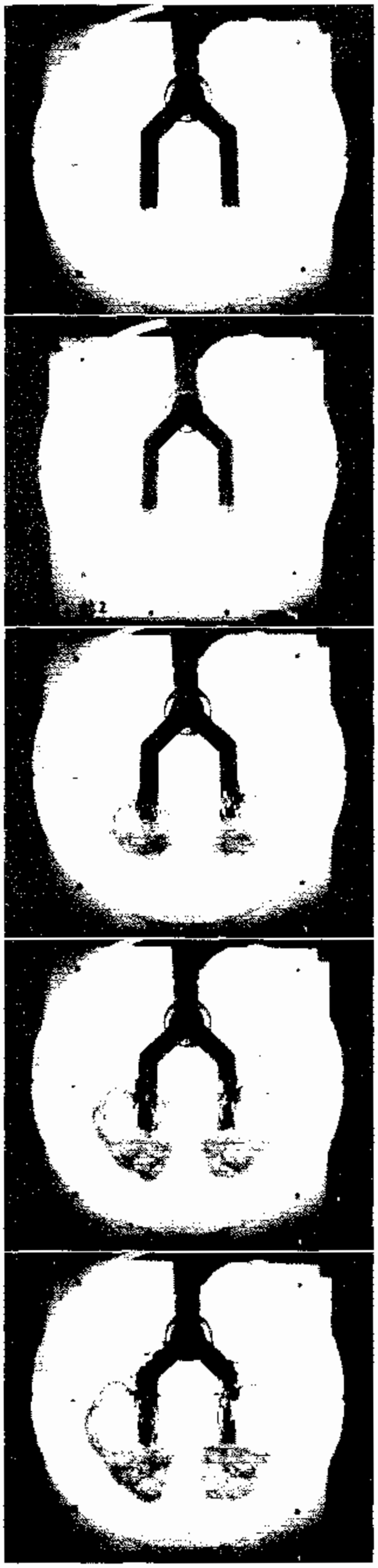


Figure 3 High-speed film from model Test 2 records wetwell pool swell under the impetus of drywell air discharge during the first 0.2 second.

ceptible in the films during this early stage due to the relatively low liquid velocities and the small water volume that is displaced.

Following vent clearing, the injected air forms a bubble below each downcomer exit. Initially, the bubbles expand into spheroidal shapes; each is slightly skewed away from the neighboring bubble, indicating that its presence is felt. Subsequently the bubbles grow into "strawberry" shapes, expanding more near the top than the bottom as air continues to feed the bubbles. The bubble center also rises because of the larger expansion rate near the top, the upward liquid velocity field, and the effect of buoyancy. Eventually, separation bubbles (air pockets) develop on the upper, slanted surface of the downcomer. These separation bubbles finally link the submerged bubble to the wetwell air space above. No energetic bubble penetration through the pool surface is seen. Also, the two adjacent bubbles never coalesce during this sequence of events.

Figure 3 also shows development of the pool swell resulting from the injection of air into the water. Initially the pool surface is in line with three horizontal markers on the face of the model. As the submerged air bubbles grow to significant size, the pool swells with a convex cross-sectional profile. During this phase, the water displacement at the wetwell boundary is approximately half that at the center. The surface is relatively flat in the central region, but it develops a slight depression immediately below the ring header just before impact. As the water strikes the header, it begins to accelerate around and eventually separates from that surface. Subsequently, the pool surface disperses into a frothy mixture of air and water.

### Analysis of results

Graphic analyses of the pool-swell process were performed at EPRI, using sequential photographs from the high-speed films. These analyses indicate that the pool surface velocity profile closely resembles the displacement profile at corresponding points in time. In addition, these analyses provide estimates of the hydraulic impact velocity against the ring header.

For Test 2, which is the closest simulation of scaled prototypical pressure histories, the impact velocity in the model test was 7.4 ft/sec. Based on the scaling rationale developed to date, this implies a prototypical impact velocity of 23 ft/sec in the reference plant, in which the average downcomer spacing is 7.2 ft. This is approximately two-thirds of the value previously estimated. It was also noted that the curvature of the pool surface at impact tends to reduce the impact load on the ring header.

The foregoing scale-model test findings were presented to the Mark I Containment BWR Owners' Group and its supporting organizations in July 1975. They, in turn, presented the results to NRC as part of a larger interim response concerning the generic functional integrity of Mark I pressure suppression systems under hypothetical LOCA conditions. The test data and analysis were taken into account in a regulatory decision at that time to allow continued operation of Mark I plants while their assessment continued.

### Continuing research

Additional research has since been sponsored by EPRI to quantify pool-swell phenomena beyond the findings summarized here. A project was initiated at JAYCOR, Inc., to perform a computer simulation of pool-swell phenomena in a downcomer unit cell similar to the SRI test model. Correlation of results with the SRI test data has been encouraging. JAYCOR's work is now being extended to a more complete model of hydrodynamic response in a Mark I pressure suppression system. In addition, an EPRI technical consultant has applied classic hydrodynamic theory to pool-swell phenomena. This is yielding a set of approximate analytical solutions to describe the kinematic response of the pool. On completion of these efforts, pertinent results will be documented in EPRI reports.

Division Report

# Fossil Fuel and Advanced Systems

Richard E. Balzhiser, Director

## Fossil Fuel Department

### FLUIDIZED-BED COMBUSTION

Commercial production of electric power utilizing a fluidized-bed boiler can become a reality by 1985. The impact of this application can be measured by the following potential advantages of the fluidized bed over conventional boilers.

- Combustion of coal in a fluidized bed of limestone, thereby controlling $SO_2$ emissions in situ
- Maintenance of comparable efficiency at lower combustion temperature, thereby reducing $NO_x$ formation
- Achievement of greater volumetric combustion and heat transfer rates, permitting a reduction in equipment size

Currently, the use of a fluidized-bed concept for coal combustion is receiving attention from several government agencies, EPRI, and individual utilities. Thus far, the result of these individual efforts has been the generation of discrete sets of data, which superficially have exhibited the potential advantages of the fluidized bed over conventional coal combustion techniques. However, in assessing the data with respect to commercial application, their value (and often their credibility) cannot currently be assessed. This problem is caused by the small experimental scale from which most experimental data have been derived or by an overly fundamental basis of experimentation and a lack of completeness in the data derived from the larger systems. Furthermore, the individual data cannot be collectively compared because of the discontinuity among experimental bases.

If the viability of a commercial fluidized-bed coal combustor is to be effectively evaluated, additional concurrent studies must be initiated. EPRI is currently engaged in substantial research intended to consolidate existing fluidized-bed combustion (FBC) technology and to develop and support new experimental projects required to provide these additional data. The immediate goal of this research effort is to develop complete and viable technology to support the design of a near-commercial-scale electric utility fluidized-bed boiler. This large unit should provide confirmation that FBC is an economic option for steam generators in a utility application. The first large unit would also verify the design and/or indicate the needed improvements for a commercial unit (400–800 Mw).

#### Technology Development

As an initial step in EPRI's fluidized-bed boiler development effort, the services of Babcock & Wilcox Co. have been enlisted to survey existing FBC technology. The intent of this survey is to obtain the following information: (1) an analysis of available technical data, (2) an analysis of existing proposed designs for utility boilers using FBC, and (3) the adequacy of this technology base with respect to the design of a utility FBC demonstration unit. This final judgment (3) will determine experimental projects required to satisfy the design criteria specified in Figure 1.

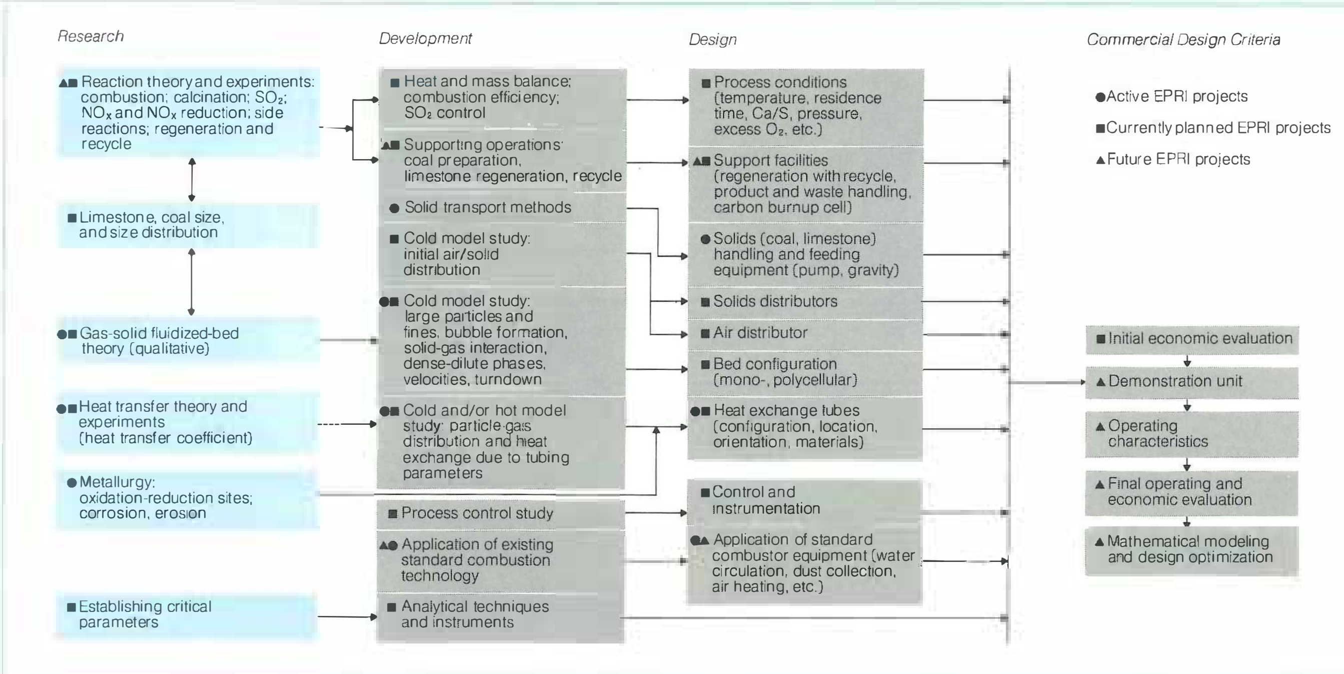
#### Current Progress

At present, existing FBC technology can be categorized as:

- Basic theory derived from small-scale experimentation (e.g., mechanics of fluid flow through a mass of monodispersed particles, heat transfer relationships, reaction chemistry mechanisms). This information is abundant, but its value is primarily qualitative due to its narrow scope (e.g., monodispersed particulate studies, single-tube heat transfer studies).
- Mathematical models predicting entire FBC systems and system parts. In studies such as these, the data output can only be as accurate as the data input. In general, since the models have been built from information existing in the preceding category, their utility is also qualitative.
- Experimental FBC pilot plants.

The incentive for applying FBC to utility-scale steam generators has been previously demonstrated through innovative work carried out by various organizations. Most recently, successful experiments were performed by Pope, Evans and Robbins on a 0.5-Mw fluidized-bed coal-fired boiler in Alexandria, Virginia. Information provided from these experiments is now being applied to the design and construction of a larger (30-Mw) test unit to be located at Monongahela Power

Figure 1 Fluidized-bed technology development. There are certain areas in which viable technology must be developed to design a successful FBC demonstration unit. Extensive experimental work has been done in several of these areas, but in most cases its value is qualitative and therefore does not directly supply design criteria.




Company's Rivesville Station in West Virginia. Pope, Evans and Robbins and Foster-Wheeler are building the Rivesville unit, with funding from ERDA. The unit is scheduled to be ready for operation early in 1976.

The early success of such projects as Rivesville will further demonstrate a viable application (although on a small scale) of FBC technology to utility-scale boilers.

### Current Limitations

Totally integrated FBC pilot plants may be "ahead of the game" with respect to demonstrating practical commercial operation, but their existence is required for development incentive. In considering criteria that must be satisfied for the design of an integrated FBC demonstration unit (and the subsequent commercial units), it is apparent that although projects such as Rivesville will be of macroscopic value, they will lack the versatility to provide detailed design criteria.

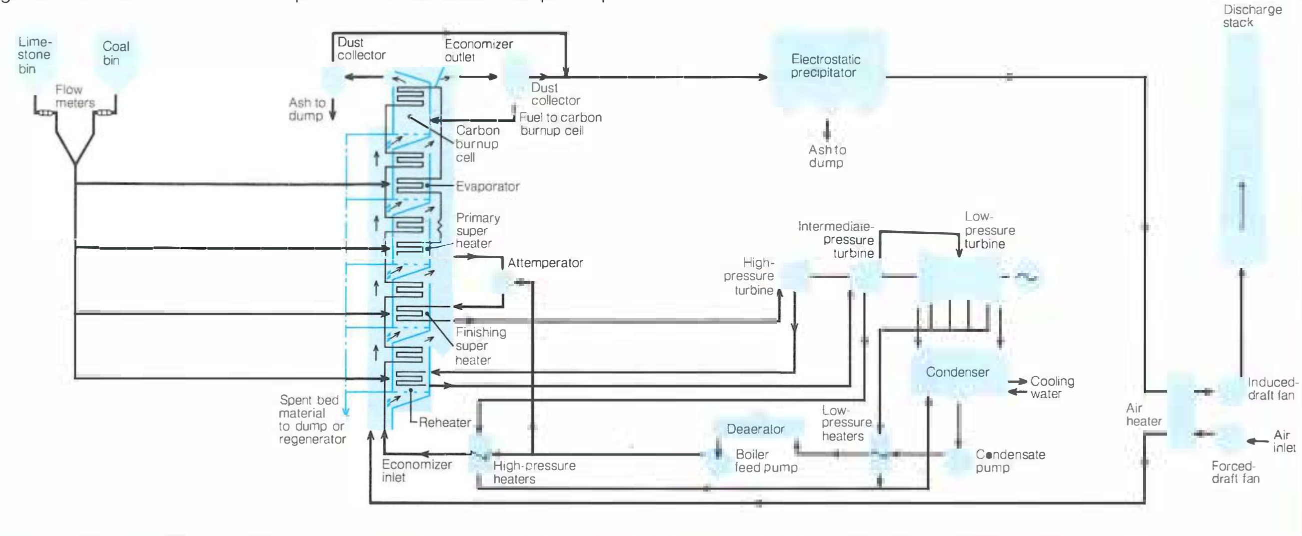
The Rivesville project (combined with previous Pope, Evans and Robbins' experimental work) can provide substantial data on processing parameters, required support facilities, and instrumentation and control techniques (Figure 1). However, with respect to critical mechanical design criteria (in particular, distribution and heat transfer), Rivesville will provide minimal design information. This is primarily due to its limited physical size and its inflexibility (resulting from the prohibitive costs of making rapid physical changes).

### Additional Development: Distribution and Heat Transfer

It is apparent that a large criteria gap will still exist with respect to a successful commercial FBC design despite success at Rivesville. For example, the study performed for EPRI by Babcock & Wilcox has thus far revealed that suitable commercial FBC design criteria relating to distribution and heat transfer do not currently exist and that R&D programs should be established. Extensive, documented experimentation (heat transfer and distribution in fluidized beds) has been performed, but its value has primarily been qualitative. This is because the data have been developed from small-scale experimentation or at low throughputs and their use has required substantial extrapolation; experiments have generally been performed over small parameter ranges (i.e., the wide range of particle sizes in FBC have not been modeled); and the data have been obtained from diverse sources, resulting in data discrepancies.

EPRI is currently supporting research studies involving heat transfer and solids distribution. These studies will apply the existing qualitative theory to a realistic FBC environment on a continuous experimental scale. Based on quantitative results from this work, funds have been appropriated to support the design and construction of a large-scale development model, which will be used to develop the large-scale mechanics of solids distribution and heat transfer, as well as a proposed commercial design for solids distribution and

Figure 2 Foster-Wheeler's concept of a fluidized-bed boiler power plant.




heat transfer equipment. The relative impact of this work will be measured by:

- The accurate characterization of experimental parameters and their proper translation to a large-scale model
- The inherent flexibility of the large-scale model (provisions for inexpensive and expedient modifications must be included)
- The fact that ~50% of the required FBC design criteria relate to materials distribution and heat transfer, and potentially can be satisfied (Figure 1)

### Necessity for Models

Recent FBC development activities have been aimed at demonstrating a total pilot plant concept. Although the success of these projects will have substantial impact on FBC credibility, their ultimate commercial utility will be limited.

Large-scale modeling is, therefore, a current necessity for developing commercial FBC scale-up criteria for the very large utility steam generators.

The greatest modeling impact will result from the development of distribution and heat transfer technology and its mechanical application to large-scale operations. *Project Manager: Terry E. Lund*

## FUELS FROM MUNICIPAL REFUSE

The disposal of municipal solid waste (MSW) has become both expensive and environmentally less acceptable. Since there are increasing calls for the conservation of natural resources and since a large portion of municipal solid waste is combustible, the recovery of energy from municipal solid waste has been receiving considerable attention from the electric utility industry. A study (*1*) recently completed by Bechtel Corp. for EPRI sought to provide:

- An up-to-date assessment of fuels derived from solid waste and their use by utilities
- Guidelines for a utility to evaluate a move into the MSW area

### Municipal Solid Waste

MSW includes household and commercial refuse. The national average daily quantity per capita is about 3 lb. Typical MSW (as received) contains 25–30% moisture and has a heating value of about 4500 Btu/lb. Both the composition and the quantity of MSW vary, depending on location and season. However, MSW processing facilities must be designed for peak rates, not for average rates.

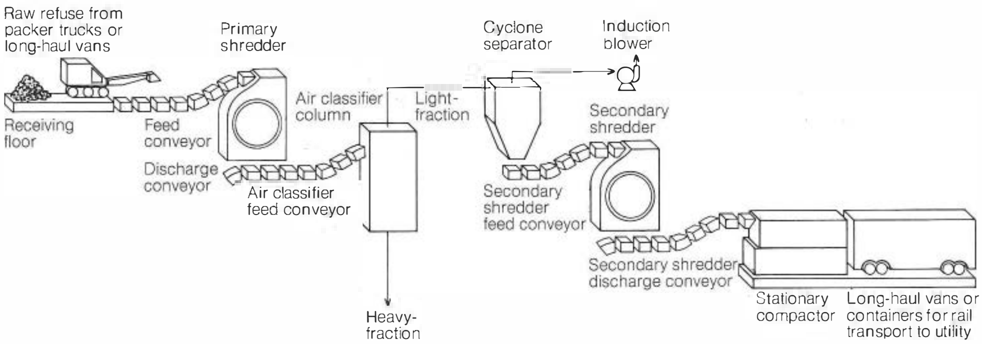
MSW must be converted to a form that is acceptable to a utility. For example, a utility may process MSW to a fuel, may purchase an MSW-derived fuel, or may even purchase steam or electricity generated from an MSW-fired boiler owned by a municipality.

A study by Gordian Associates (*2*) indicates that no more than 6–7% of the fossil fuel requirements of the utility industry could be met with MSW. However, this figure requires some qualification.

- Because energy is consumed in processing MSW into a fuel, not all the energy available in as-received MSW can be used.
- It is not likely that the total amount of MSW generated in a community would be available for power production.
- Not all the boilers listed in the Gordian study are suitable for supplemental firing with MSW.

Estimates in a recent study by TVA (*3*) are that only 2% of the nation's electric power requirements can be provided by MSW.

Figure 3 Preparation of MSW as a solid fuel.




**Preparation of MSW as a Solid Fuel and Supplemental Firing**

Several suppliers offer processes for the preparation of MSW as a solid fuel (MSW light-fraction fuel). Most have proposed light-fraction fuel rather than such other forms as pellets and briquettes. Figure 3 is a generic process diagram for the production of MSW solid fuel.

The composition of a typical MSW light-fraction fuel is given in Table 1. The heating value of this fuel is typically 5000–6000 Btu/lb. A comparison of coal and a typical MSW light-fraction fuel is given in Table 2.

The process of recovering energy by burning MSW light-fraction as a supplementary fuel in power plant boilers has been under investigation by the city of St. Louis and the Union Electric Company. The original development was supported by EPA. The results of a demonstration at Union Electric's Meramec plant have been encouraging. The prepared solid waste was burned in suspension with coal in two 125-Mw tangentially fired boilers.

At rated load, the quantity of solid waste for each boiler (equivalent in heating value to 10% of the coal) is about 12.5 t/hr or 300 t/day.

Experience at the Meramec plant has so far indicated that corrosion is not a major problem with supplemental firing. However, short-term corrosion-test results are sometimes misleading. The existing boiler combustion controls easily accommodate the variations of solid waste quantity and quality by varying the amount of coal fired in the boiler.

Electrostatic precipitator performance was tested at Meramec with and without refuse firing. The early results reported for these tests were inconclusive. Additional tests have been performed to resolve the uncertainty in the data but the results have not yet been made available.

When MSW light-fraction is fired as a supplementary fuel, an

**Table 1**

**MSW LIGHT-FRACTION SOLID FUEL**

| *Component* | *w/o* |
|---|---|
| Paper | 55.0 |
| Food wastes | 16.0 |
| Yard wastes | 13.7 |
| Glass, ceramics | 2.7 |
| Plastics | 1.8 |
| Textiles | 2.5 |
| Wood | 2.6 |
| Leather and rubber | 1.8 |
| Miscellaneous | 3.9 |

**Table 2**

**COMPARISON OF COAL AND MSW LIGHT-FRACTION FUEL**

| | *Coal Fired at Meramec* | *Typical Sub-Bituminous Coal* | *MSW Light-Fraction Fuel* |
|---|---|---|---|
| Content (%) | | | |
| Moisture | 10.0 | 21.0 | 18.0 |
| Ash | 9.0 | 6.0 | 14.0 |
| Chlorine | 0.05 | – | 0.07 |
| Sulfur | 3.4 | 0.5 | 0.1 |
| As fired, Btu/lb | 11,315 | 9,570 | 5,784 |

efficiency loss, primarily caused by the addition of unheated transport air, may be experienced. This loss is typically 1.5% and 2.5% for 10% and 20% supplemental fuel firing, respectively.

Tests of supplemental firing of a powdered light-fraction fuel with residual oil are being planned by several utilities.

### Other Methods for Refuse Utilization

MSW may be pyrolyzed to low- or medium-Btu fuel gas. Union Carbide's Purox process for the production of medium-Btu gas is being demonstrated at a 200-t/day plant in South Charleston, West Virginia. A 1000-t/day plant using Monsanto's Landgard process is expected to become operational in August 1976 in Baltimore, Maryland.

"Mining" of gases from anaerobically digested landfills has been carried out by Los Angeles Water and Power Department and NRG, Inc.

Occidental Research Corp. has been developing a process for the pyrolysis of MSW to a fuel oil and is constructing a 200-t/day demonstration plant near San Diego, California.

MSW light-fraction fuel can be burned in a fluidized bed of inert material. The hot combustion gases are then passed through a gas turbine generator set. This approach, supported by EPA, is being developed by Combustion Power Co.

### Efficiencies and Cost Estimates

The relative thermal efficiencies of each processing option in recovering the energy value of MSW as fuel and the overall efficiencies when these fuels are converted to electric power are summarized in Table 3.

The capital costs for the four fuel preparation processes and for fluidized-bed combustion power generation are shown in Table 4 for both fuel preparation facilities and fuel utilization facilities. Since these estimates apply to a wide range of processes—from commercial processes to those that have not been demonstrated—their certainty varies, and they are intended for comparison purposes only.

Table 4 also includes operating costs for the preparation of MSW fuels or the generation of electric power. In preparing this table it has been assumed that the fuel preparation facilities are owned and operated by a municipality.

Transportation charges incurred by the fuel processing facility depend on its location relative to the present disposal site and transportation distance to the final fuel user. Transportation was not included in the operating costs shown in Table 4.

A credit for tipping, or dumping, fees must also be determined for each case. Because of different hauling distances, the actual tipping fee may be different from the current tipping fee at the present disposal site. Tipping fees may be as low as $2–$3/t or as high as $15/t, as in congested metropolitan areas.

**Table 3**
**COMPARATIVE PROCESS EFFICIENCIES**

| *Process* | *Fuel Preparation* | | |
|---|---|---|---|
| | *Gross Thermal Efficiency* %[1] | *Net Thermal Efficiency* %[2] | *Overall System Efficiency* %[3] |
| Solid fuel | 93 | 85 | 29 |
| Pyrolysis to gas | 79 | 66 | 22 |
| Pyrolysis to oil | 57 | 46 | 16 |
| Anaerobic digestion of landfilled MSW | 6–34 | 6–34 | 2–12 |
| Fluidized-bed combustion gas turbine | – | .. | 26[4] |

1. Energy contained in fuel produced divided by energy contained in raw MSW
2. Energy contained in fuel produced minus power required to process refuse divided by energy contained in raw MSW
3. Overall system efficiency for process types 1–4 calculated assuming fuel burned in power plant with a heat rate of 10,000 Btu/kwh calculated for these processes by multiplying net thermal efficiency by 34%
4. Gross electrical output: 31 Mw; net electrical output: 27.9 Mw

**Table 4**
**COMPARATIVE CAPITAL INVESTMENT AND ANNUAL OPERATING COST ESTIMATES**
(MSW capacity 1000 t/day)

| *Process Type* | *1* | *2* | *3* | *4* | *5* |
|---|---|---|---|---|---|
| Description | Solid fuel | Pyrolysis to gas | Pyrolysis to oil | Anaerobic digestion of landfilled MSW[1] | Fluidized-bed combustion gas turbine |
| Fuel preparation facilities, capital investment ($ million) | 11 | 26 | 23 | 5 | 24 |
| Operating cost[2] | | | | | |
| Annual cost $/t MSW | 5.97 | 21.82 | 17.00 | 4.09 | 14.79 |
| Annual cost $/$10^6$ Btu | 0.72 | 3.09 | 3.37 | 1.42 | .. |
| Fuel utilization facilities, capital investment ($ million) | 4 | 1 | 2 | .. | .. |

1. Gas recovery rate of 3.1 ($10^9$) Btu/day
2. Excludes tipping fees and transportation charges

### Outlook

The burning of fuels derived from MSW in utility boilers appears to be technically feasible. An assessment of an MSW-fuel-recovery system in any particular location will be unique for that location in that there are local options that must be considered. An intent of the Bechtel study was to provide guidelines so that individual utilities could make preliminary evaluations of the general feasibility of the MSW-fuel-recovery systems.

The most developed MSW-fuel-recovery system is the preparation of a solid fuel followed by supplemental firing in a boiler. The technical issues on the use of this solid fuel in boilers as a supplementary fuel are not development problems but mainly engineering problems that must be solved through design modifications. Long-term corrosion effects and the effects of increased particulate loading on precipitator performance require further investigation.

Within the assumptions made in estimating the capital and operating costs, none of the process options is competitive with the production of a solid fuel from MSW for supplemental firing. Even this option will be economical only if transportation charges are low and tipping fees are high.

Tipping, or dumping, fees and transportation costs are major cost elements in any fuel recovery from MSW systems. These costs are highly local.

The environmental issues that have been raised by the supplemental firing of fuels from MSW in power plant boilers have not yet been fully resolved. However, local institutional issues may be the most significant impediments to the widespread use of MSW as a utility fuel source. *Program Manager. Michael Maaghoul*

### References

1. EPRI 261-1. *Fuels from Municipal Refuse for Utilities; Technology Assessment,* Final Report, prepared by Bechtel Corp., March 1975. (Available from National Technical Information Service. PB 242 413).

2. "Where the Boilers Are," a report prepared by Gordian Associates for EPA, February 1974.

3. Presentation by TVA at the National Resource Recovery Seminar, Knoxville, Tennessee, October 17, 1975.

## Advanced Systems Department

### ADVANCED CYCLES

In the search for improved methods of converting heat to electricity for utility power generation, a variety of advanced energy conversion systems have been proposed and investigated over the years. These technologies continually compete for limited research funds, and the relative merits of each proposed system must be reviewed continually to establish its proper level of support. In addition, broad-based research and development programs are required for each technology to solve technical problems and to lay a foundation for commercialization.

Activities in the advanced cycles subprogram concern both the continuing evaluation of the various technologies and the support of research bearing on the feasibility of promising concepts. These activities are intended to provide a basis for lending industrial guidance to nationwide development efforts and for assessing the potential impact of emerging technologies on the electric utility industry. This article outlines recent progress in some of these activities.

### Current Evaluation

The characteristics of the various advanced cycles in their projected applications on electric utility systems are being reviewed in EPRI's comparative study and evaluation of advanced cycle systems (CSEACS). This study is being performed by General Electric Co. in conjunction with NASA's energy conversion alternatives study (ECAS), which concerns advanced cycles with heat sources using coal or coal-derived fuels. CSEACS complements the NASA project by incorporating systems using oil-fired or advanced nuclear heat sources. Projected energy conversion system characteristics and technical barriers to their commercialization are being assessed on a consistent basis. The results will be used in determining proper research objectives and priorities for the energy conversion technologies.

The CSEACS effort is being carried out in three phases and is scheduled for completion later this year. This study initially addressed the following energy conversion systems in representative applications: advanced combined-cycle gas-steam turbines, closed-cycle gas turbines using helium or carbon dioxide, magnetohydrodynamic (MHD) cycles, metal vapor turbines, thermionic devices, and fuel cells. The first phase of the effort, completed in January, was mainly directed toward the establishment of consistent, comprehensive procedures for evaluating these energy conversion concepts. The evaluation procedure includes (1) a ranking of the concepts in regard to specific criteria of R&D requirements and plant economics and of technical characteristics in relation to utility objectives and (2) cost-benefit analyses for a number of the concepts.

Preliminary evaluations of the various energy conversion systems were carried out in Phase 1. Based on the results, a maximum of six promising systems will be studied in further detail in the second phase of CSEACS. Unfortunately, the final data and system selections resulting from Phase 1 were not available at the time of this writing, but some interesting general results are discussed presently.

The detailed studies during Phase 2 will include conceptual plant designs and economic analyses, along with an overall assessment of R&D requirements for each concept. This detailed evaluation, in turn, will lead to a selection of up to three specific concepts for detailed cost-benefit analyses in the third phase of the project.

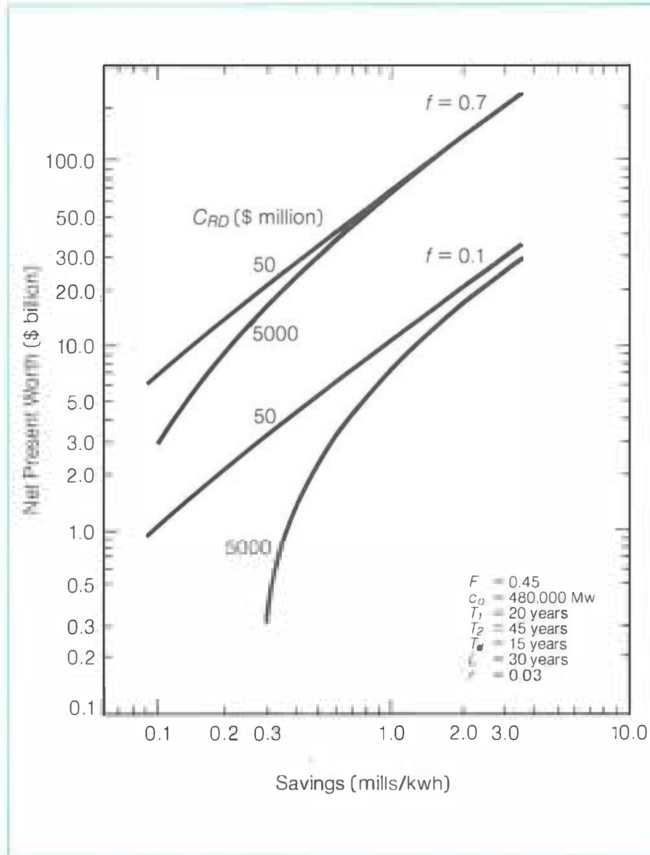
One preliminary result of Phase 1, arising from the development of the cost-benefit analysis procedure, is worth discussing at this point. The many factors affecting the net present worth (benefits minus costs) of a given advanced energy conversion technology can be summarized, for our purposes, in terms of three critical parameters: $C_{RD}$, the cost of R&D leading up to the first plant installation; $T_1$, the duration of this required R&D effort; and $f$, the percentage of new generating capacity added yearly in the form of the new technology after its commercial introduction.

Suppose that an advanced technology shows a savings in power generation costs of at least 1 mill/kwh over conventional plants. Suppose also that this advanced technology has a limited lifetime and will be superseded by a superior technology about 30 years after its introduction. Finally, suppose that the net discount rate (the difference between interest rates and the rate of inflation) remains at 3.5%, indicating moderate economic conditions over the lifetime of the technology.

With the above assumptions, we find that variations in $C_{RD}$ (R&D costs) have a negligible effect on the net present worth of the advanced technology because the net savings from installations of the advanced power plant generally overwhelm the initial R&D investment. This means that great investments in R&D to achieve even modest improvements in power generation costs can be justified.

We also find that $T_1$ (development time) can have an important influence on the net present worth. This is not surprising, since early commercial introduction enhances the total savings derived from a technology having a limited lifetime. This implies that, with all other factors remaining unchanged, a rapid R&D program is desirable.

Figure 4 Net present worth of an arbitrary energy conversion technology shown as a function of projected savings in power generation costs over conventional technology. Curves indicate the various values of $C_{RD}$, the cost of required research and development, and of $f$, the percentage of new plants using the new technology. $F$ is the average plant capacity factor; $c_0$ is the total current installed capacity; $T_1$ is the elapsed time up to the first commercial installation; $T_2$ is the elapsed time up to the last commercial installation; $T_d$ is the doubling time of total power demand; $L$ is plant lifetime; and $r$ is net discount rate.




The most interesting result, however, is the influence of $f$ on the net present worth of the technology. A change in this parameter, which might be termed the market penetration of the technology, produces a change in the net present worth that is roughly twice as large as that produced by a proportionately equal change in $T_1$, all other factors remaining unchanged. This result implies that, in general, it is not as important to achieve early demonstration of a promising technology as it is to achieve early, significant market penetration.

In terms of R&D requirements, we reach the conclusion that choosing the right demonstration plant design is crucial to the realization of maximum benefits from a technology expected to become obsolete at some future time. A poor choice of the design for a demonstration plant could severely limit the benefits to be gained from the technology by limiting its market penetration rate, particularly in the early years of its utilization. This philosophy has guided the advanced cycles subprogram in the past, notably in the planning of an overall R&D program for open-cycle MHD, the advanced energy conversion concept receiving top attention in the subprogram. It is significant that the CSEACS results discussed above are lending support to such earlier planning efforts.

**Open-Cycle MHD**

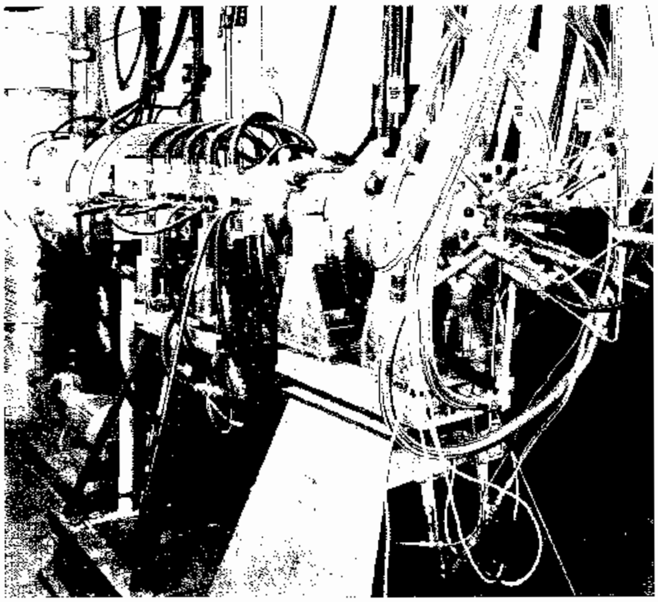
The above result affirms the importance of market assessment studies now being implemented in relation to open-cycle MHD, a technology exhibiting a wide variety of possible plant configurations. These studies, called the operational and systems analyses for open-cycle MHD power generation, will project the market penetration of promising plant configurations and will provide needed data on the R&D requirements of each configuration. This information will be important both in choosing a proper demonstration plant design and in projecting the possible impact of open-cycle MHD technology on the industry and the nation.

An open-cycle MHD plant basically operates by passing hot (up to 5000°F) combustion gases through a duct, called an MHD generator duct, situated between the poles of a powerful magnet. The magnetic forces induce a flow of dc electric current through the gas and into electrodes located on opposite walls of the generator duct. This electric current is converted to ac power and is fed into the electric utility grid. Power plants incorporating MHD generators offer the potential for direct use of coal at thermal efficiencies in the range of 50–55%, and perhaps higher.

The emphasis of the open-cycle MHD development program is on the utilization of coal, our most plentiful fossil fuel. The use of coal will probably require the MHD generator to withstand not only the hot combustion gases and the severe electric arcs expected to be present in the generator, but also the flow of molten coal slag (mineral matter liberated from the coal during combustion) through the generator and other components.

A key issue in the development program has been the search for adequate materials and designs for the generator walls. The most promising approach appears to be to find wall materials compatible with coal slag and to use a layer of slag on the walls as protection against the arcs and high gas temperatures. EPRI projects at Stanford University and at AVCO Everett Research Laboratory, Inc., located near Boston, are generating laboratory data in an effort to define acceptable generator operating conditions using coal slag for wall maintenance.

Figure 5 Electrode maintenance test channel at AVCO Everett Research Laboratory, Inc., which was built and is being used under an EPRI contract to study coal slag behavior in open-cycle MHD generators.



The AVCO project uses a simulated MHD duct, lacking a magnet, to study the behavior of coal slag in the generator and to help define the requirements for wall materials compatible with slag. Eventually, this information will also be used in establishing design goals for coal combustors and other components of MHD plants. These experiments have already identified the probable requirements for developing a stable slag coating in the generator. The major emphasis of this project is now shifting toward helping to define the proper way of using the slag layer in terms of design requirements for the generator and other components.

At Stanford University, a similar facility is being used in parallel to investigate the effects of coal slag on the electrical operation of the channel and eventually to test the results in a model generator. The Stanford work is also aimed at the development of a variety of advanced optical techniques for measuring important parameters in the generator. Recently, arcs produced by an imposed electric field were photographed in the simulated generator duct. This achievement will lead to important insights on the behavior of arcs in actual generators. Also, a novel device is being developed to allow extremely precise measurements of slag layer thicknesses.

The cooperative efforts of these two projects, in conjunction with related efforts sponsored by ERDA, are contributing to the rapid improvement in understanding MHD generator design requirements. These and other EPRI MHD activities are making a significant impact on the direction and progress of the national effort to develop this promising technology.
*Project Manager: Paul S. Zygielbaum*

Division Report
# Nuclear Power
Milton Levenson, Director

## PLUTONIUM RECYCLE

Experience indicates that the behavior and safety characteristics of mixed oxide ($MO_2$) fuel is generally very close to that of $UO_2$-based fuel. There are no apparent performance limitations created by the addition of the moderate amounts of $PuO_2$ to $UO_2$ that would be typical of plutonium recycle.

The EPRI Plutonium Recycle Program has focused on developing an expanded base of performance data and on increasing statistical levels. Most important is the need to develop and prove out the analytical methodology to quantify potential differences in some details of fuel behavior. This quantification is required for licensing calculations and to permit optimizing fuel design for the reliability and economics of plutonium recycle.

Table 1 outlines the current program and lists the ongoing projects and their contractors. These projects represent a balanced effort on neutronics, fuel behavior, and fuel modeling.

RP396 (jointly funded with a group of industrial sponsors) was initiated in recognition of the need to extend previously obtained $UO_2$ densification results to $MO_2$ fuel, which is fabricated by different processes and has differences in microstructure from $UO_2$ fuel. The effects of thermal history and of irradiation on the microstructure and homogenization of $MO_2$ fuels will also be investigated.

A project nearing completion, RP72-2, is providing a detailed characterization of the performance of $MO_2$ rods irradiated in the Big Rock Point reactor. Detailed metallographic examination of fuel rod sections and microprobe analysis of fission product distributions are being made.

Under RP72-2, five "island design" assemblies were designed and fabricated for insertion in the Quad Cities-1 reactor. RP497 will provide both nuclear and performance data from these assemblies, which have now completed one cycle of irradiation. Interim (nondestructive) and destructive examinations will be carried out on both the annular and the solid pellet rods contained in the $MO_2$ fuel. The first set of poolside examinations and gamma scans has been completed, and selected rods have been removed for isotopic analysis and for possible postirradiation examination at a later date.

**Table 1**
**EPRI PLUTONIUM RECYCLE PROGRAM**

| *Research Project* | | *Contractor* | *Comments* |
|---|---|---|---|
| 72-2 | Use of Plutonium in Water Reactors | General Electric Co. | Postirradiation examination of Pu assemblies |
| 118 | Advanced Recycle Methodology | Nuclear Associates International Corp. | Development of analytical capability for analyzing Pu recycle |
| 300 | Strategies for Plutonium Utilization | Stanford University | Methodology for fuel cycle decision making with Pu recycle |
| 306 | Multiple-Cycle Plutonium Utilization | Exxon Nuclear Co. | Prototypical irradiations in Big Rock Point reactor |
| 310 | Study of a Denatured Plutonium Fuel | General Electric Co. | Evaluation of the feasibility of a "denatured" fuel cycle |
| 348 | Clean Critical Experimental Benchmarks | Battelle, Pacific Northwest Labs. | Benchmark data for testing nuclear data |
| 396 | Plutonia Fuel Densification | Battelle, Pacific Northwest Labs. | Extension of $UO_2$ project to develop data base for $MO_2$ modeling |
| 397 | LWR Fuel Rod Modeling Code Evaluation | Combustion Engineering, Inc.; O'Donnell & Associates, Inc.; Science Applications, Inc.; S. M. Stoller Corp. | Related program, currently limited to $UO_2$ fuel, but with later applicability to $MO_2$ fuel |
| 497 | Quad Cities-1 Plutonium Recycle Measurements | General Electric Co. | Prototypical irradiations in Quad Cities-1 |

RP306 is a cooperative project with Exxon Nuclear Corp. Under a contract with Consumers Power Co., Exxon has designed and fabricated a number of $MO_2$ assemblies presently being irradiated in the Big Rock Point reactor. As of the beginning of 1976, 22 $MO_2$ assemblies of two different designs were operating in the core. The scope of the project includes monitoring the irradiation history of the $MO_2$ assemblies and confirmation of the calculated (small) changes in reactor operating parameters. The fuel performance will be monitored nondestructively at each cycle shutdown, and some destructive analyses, including isotopic analysis, will be carried out. It is planned that the plutonium from four of the assemblies will be recovered after completion of their full-life irradiation. New assemblies will be made and operated to obtain data on the nuclear behavior of recycled plutonium. *Program Managers: B. A. Zolotar, J. T. A. Roberts*

**CORROSION DAMAGE IN STEAM GENERATORS**

Several types of corrosion damage are currently a chronic problem in recirculating-type nuclear plant steam generators. The probable cause of this damage is the local high concentrations of aggressive chemicals, even though only trace amounts are present in feedwater. Of the many factors that contribute to this condition, one of the primary sources of the aggressive chemicals is the occasional inleakage of incompletely purified condenser cooling water into the secondary system. A wide variety of trace chemicals can find their way into feedwater, depending on the source of condenser cooling water and the specific feedwater treatment and cleanup system used.

EPRI is currently sponsoring a program (RP404–1) to characterize the secondary system chemistry in five nuclear plants, particularly during periods when inleakage is occurring. The plants were selected to provide a range of operating conditions: (1) with and without prior operation with phosphate feedwater treatment, (2) with freshwater and saltwater condenser cooling, and (3) with and without full-flow condensate demineralizers. The plants being measured are Prairie Island-1 and 2, Surry-2, Turkey Point-4, and Calvert Cliffs.

The specific types and rates of corrosion damage in steam generators will also be determined and correlated with the chemical history. The information obtained will permit the setting of more realistic limits on the chemical control requirements of secondary systems.

A large volume of data has been obtained and initial correlations to observations are being developed. Program review meetings are periodically held with participating utilities to study program results and to discuss the interpretation of data. *Program Manager: L. J. Martel*

**STUDY EVALUATES INDUSTRY INSPECTION PRACTICE**

The occasional occurrence of stress corrosion cracks in bypass lines and core spray lines on boiling water reactors (BWRs) has made it desirable to quantify the response of code-approved ultrasonic methods to such "tight" cracks. Present inservice inspection practice, as required and defined by Section XI of the ASME Code, consists of using pulse-echo ultrasonics to detect and define the nature of flaws in primary system piping.

Nearly all the stress corrosion cracks have occurred within $\frac{1}{8}$–$\frac{3}{4}$ in. from weld root on the inside surface of the pipe. The geometric reflectors present and the intergranular nature of the flaws provide a more complex situation for interpretation of the ultrasonic signals than the side-drilled hole blocks typically used for standards.

To quantify the ability of the code-approved method to detect such flaws, EPRI conducted a technical, "round robin" evaluation of actual piping removed from operating plants, including both cracked and uncracked pipe samples (TPS-75-609). Five industry teams performed the examinations. Because of measurable radioactive contamination in the pipes, the imposed working conditions simulated practical field conditions rather than ideal lab conditions. In addition to the evaluation of the flaw detection and analysis capability of each group, the variables of code interpretations, procedures, techniques, standards, equipment, and levels of operator training were observed.

The ultrasonic inspection was repeated, using a reference procedure defined by EPRI, to eliminate some of the variation caused by differences in practice within the code-approved range. Radiography of all pipes has also been done. Destructive examination, which is required to fully define flaw sizes and locations, is underway. The preliminary result is that each of the ultrasonic inspections found indications of essentially all of the known flaws (as determined by dye penetrant and by radiography), but there was some variation in interpretation as to whether further confirmation is needed to establish the importance of the indications. Extensive observations were made of procedures used for obtaining, recording, and interpreting the data. When correlations with destructive examinations have been completed, some guidelines will be available on the best and preferred assurance of obtaining highly reliable inspection data. *Project Manager: E. R. Reinhart*

**OXYGEN CONTROL IN BOILING WATER REACTORS**

EPRI is currently sponsoring several projects related to oxygen reduction in BWR primary coolant (RP311-1, RP706, RP449-3). Significant levels of oxygen are necessary, along with sensitization and high residual (or total) stress levels, to produce cracking as observed in some bypass and core spray lines of BWRs. Tests on laboratory coupons indicate that even at the levels of a few parts per million of oxygen, the time to initiate cracks can become up to 40 times shorter than at normal steady state oxygen levels (about +0.2 ppm). The primary aim of these projects is to minimize the occurrence of oxygen transients that have been found to reach levels 10–20 times higher than normal steady state operation.

Recent test results show that hydrogen peroxide is also formed at relatively high levels during this phase of operation. Data will be obtained to quantify the benefit of reducing oxygen and hydrogen peroxide as they relate to the rate of initiation or growth of intergranular stress corrosion cracking in Type 304 stainless steel. Such cracks occur mainly in the weld-heat-affected zones.

It is known from prior work that oxygen transients can be effectively reduced by several procedures, such as deaeration of makeup water and (in PWRs) the addition of hydrazine during plant startup. One of the current projects includes testing the relative effectiveness and practicality of various combinations of control methods. Most of the significant test results from these projects are expected to be available by the end of 1976. *Program Manager: L. J. Martel*

**SUBCRITICAL CRACK GROWTH IN FERRITIC MATERIALS**

A novel technique for determining the elastic-plastic fracture toughness of ferritic materials is being investigated by Combustion Engineering, Inc., (RP232-4).

Conditions at the onset of crack extension must be known in order to determine meaningful initiation fracture toughness. When toughness is low, reasonably small specimens may be applied effectively. As toughness increases (e.g., increasing test temperature), it becomes impossible to accurately measure the value of toughness because the crack front extends at subcritical loadings before instability is observed (Figure 1). The development of experimental techniques to circumvent this problem is necessary.

In the past, a multispecimen technique has been required. The new technique concentrates on the detection of crack growth from a single specimen. Such information is generated simultaneously with the conventional load-deflection record, and appropriate data manipulation leads to accurate initiation toughness values. Because only one specimen is required, the technique has the potential for providing meaningful toughness data from a minimum of test material. In addition, small specimen testing may be defendable even for elastic-plastic material behavior. The project scope includes:

- The demonstration of the accuracy and repeatability of the detection technique
- The design and fabrication of hardware and software to automate the technique
- The determination of elastic-plastic fracture toughness of three production SA533 Grade B, Class 1 plates, three production automatic submerged arcs, and three manual metal arc weldments of sections that are six inches or larger

The technique uses an ultrasensitive piezoelectric crystal load cell to detect load perturbations resulting from void formation and coalescence associated with plastic fracture initiation and growth. A correlation is made between the load perturbations and the fracture morphology, using both conventional metallography and electron fractography.

Preliminary results (Figure 2) are encouraging and indicate the basic feasibility of this technique. In Figure 2, fracture toughness ($J_{1c}$) determined by the new method is compared with fracture toughness determined by the traditional multispecimen technique. It can be seen that similar results are obtainable, regardless of the method applied.

Should this technique be proved successful, it could be used effectively in testing irradiated materials. The paucity of irradiated specimens generally precludes use of the traditional multispecimen test technique. Hence, the new technique may provide a means for complete fracture characterization of irradiated materials. *Project Manager: R. E. Smith*

Figure 1 Two examples of subcritical crack extension occurring prior to fracture instability. The specimen on the left was heat treated to provide better definition of crack extension.

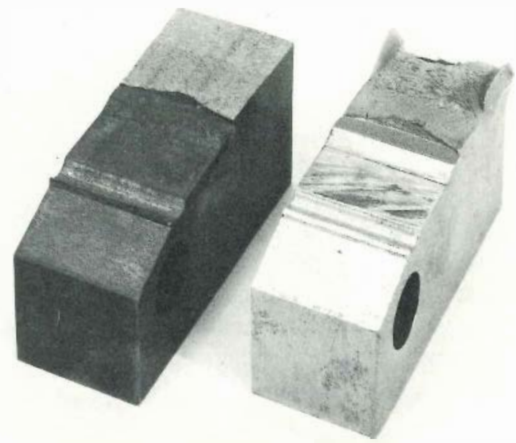
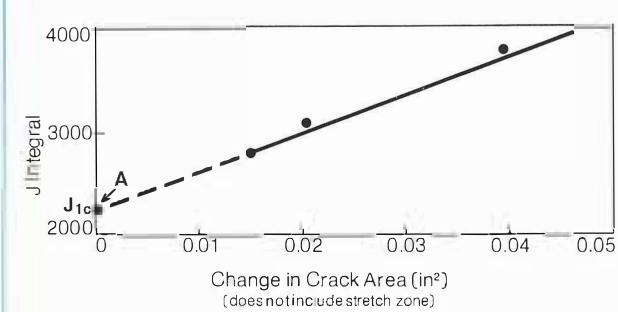


Figure 2 Automatic submerged arc weldment for SA533-B-1 plates; test temperature, 75°F. Point A was previously determined by Combustion Engineering's tandem-load cell system ($J_c$ = 2270 in-lb/in²).



# Energy Systems, Environment, and Conservation

René H. Malès, Director

## ENVIRONMENTAL ASSESSMENT DEPARTMENT

### Cost-Benefit Analysis

The objectives of this subprogram are to facilitate the consideration of environmental factors in the choice among alternative sites, technologies, and energy systems, and to suggest pollution control strategies that will minimize adverse environmental effects at least cost. Cost-benefit analysis is a method of comparing the (marginal) costs of following one alternative with the (marginal) benefits to be achieved as a result of this alternative. The alternative could be a control procedure, such as flue gas desulfurization, or it could be a level at which some environmental standard is set. Economic theory indicates that the optimal level would be one at which the marginal benefits of control would equal the marginal costs of control. Cost-effectiveness analysis is another term for cost-benefit analysis when it is used to find the optimum among alternative sites, technologies, and energy systems.

In carrying out cost-benefit and cost-effectiveness analyses, it is desirable to have a common denominator for both costs and benefits. The usual common denominator is dollars. But in some cases, precise or complete monetary measures are not always necessary. If the estimates of the damage and benefits are few and biased in the same direction for each alternative, then a direct comparison of the physical values can be made. Also, when the differences between the benefits and costs are very large, gross estimates of the benefits can be tolerated, requiring little refinement of monetary estimates.

The more usual case of such analyses, however, turns on the reliable translation of both physical costs and benefits into monetary effects. It may appear simple and straightforward on the surface, but estimation of costs, particularly environmental damage, is especially difficult. It is difficult to reliably estimate even the nature of certain environmental effects, let alone their extent. It is even more difficult to translate these into generally acceptable monetary terms. The questions are not only on the probability of damage but on the value of impacts on such diverse subjects as human health, unencumbered landscapes, and healthy flora.

The necessary initial steps in this program are the integration of information on environmental impacts and the development of a methodology to quantify the various impacts into monetary terms. Work is underway in both areas, with preliminary emphasis being placed on the environmental impacts of coal-burning power plants. In RP755-1, a methodology will be developed and applied to estimate air pollution damage from coal-burning plants. Information about air pollution effects will be collected and utilized to estimate the damage from air pollution in an urban and a rural air basin, and these damage estimates will be converted into monetary terms. RP755-2 will stress the esthetic component of air pollution damage. In particular, methods will be developed to estimate the values that society attaches to alternative degrees of visibility in the western states.

The results of these two studies hopefully will lead to a cost-benefit analysis methodology that will be an aid in determining the optimal level of air pollution control for coal-fired power plants. Future work will also include the comparison of the environmental impacts of alternative emission control strategies. A related line of future work will be the study of siting policies, including a comparison of fossil fuel energy centers compared with dispersed power plant siting. *Project Manager: Ronald Wyzga*

## ENERGY SYSTEMS MODELING PROGRAM

### Model Application and Analysis

There was a time when looking ahead was a reasonably straightforward matter for the electric power industry. The future could be estimated by simple projections of the historical growth curve. Fuel prices were relatively stable and environmental factors were not of primary concern.

Changing times bring changing problems and needs. The effects of conservation and higher prices on the future demand for electricity can only be guessed. Resource requirements of advanced technologies proposed for generating systems of tomorrow are uncertain, and the time needed to perfect these technologies is open to question. Costs and environmental impacts are far from being well delineated or understood, and the capital requirements of new technologies are of imposing magnitude. The effects of these large capital requirements, along with continuing changes in the prices, availabilities, and consumption of energy, need careful study.

*Resort to Modeling* Under the circumstances, it is not surprising to find analysts and planners looking for the most advanced and comprehensive tools available. Big problems invite sophisticated methods of solution. Potentially the most sophisticated planning tool yet devised is the computer model. As we use the term here, a model is a programmed representation of a system under study. The model allows exploration of the properties attributed to the system under varying assumed conditions.

The system being modeled may be a smokestack, a single generating station, a complete utility, the electric power industry, or the whole economy.

One purpose of modeling is straight economic forecasting. Several large macroeconometric models of the economy have been developed in recent years to forecast national income variables. The Chase Econometrics, Data Resources, and Wharton models are three of the best known and most widely employed. These models can be used also for *conditional* forecasting, which means exploring the implications of different future scenarios and alternative policy actions.

The Brookhaven Energy Modeling System is another large and well-known model. It takes a different methodological approach from macroeconometric models—mathematical programming rather than econometrics. It is an optimizing, not a forecasting, model, and it focuses on the assessment of energy technologies—on their resource ramifications and environmental impacts. Government agencies have been making extensive use of all the aforementioned models, as well as models of their own creation and adaptation, such as FEA's Project Independence Evaluation System (the so-called PIES model). FEA and ERDA are among the most active sponsors and appliers of models. The professionals involved in modeling activities within these two agencies alone number well into the hundreds, and their ranks are growing.

*Models as a Technology* A model is a technology whose nuts and bolts are abstract symbols and mathematical expressions. To perform the manifold calculations required to go from input to output—from data and assumptions to results—a typical model depends on the technology of the automatic digital computer. Whereas the computer is a "hard" technology whose concepts have been realized in physical hardware, the model is a "soft" technology. Its concepts are realized in digitized information and programmed relationships.

Miniaturization has not come to modeling as it has to many hard technologies. Quite the opposite is the pattern. As the problems get larger and as the need for refinement increases, the work models are put to grows in magnitude. Models tend to expand geometrically in size and number. Models are asked to examine a problem at varying levels of detail, from several sides, in different ways. Multiple models result. A current trend is to link models into what can become gargantuan systems of interconnected components that feed information to one another and mediate each other's behavior. As their dimensions increase, models and systems of models can become difficult to comprehend. It is not always clear just why a model produces the results it does.

Thus, at the same time that greater reliance is being placed on models, the expansion in their size and complexity increases the danger of misunderstanding and misconstruction. Modelers are limited in their ability to correct the problem. Their deep involvement in the model-building process robs them of the detachment and innocence of the outsider. Decision makers, although having an outsider's perspective, lack the time and often the training to delve into the intricacies of the models. There is a need for a third party—a modeling analyst who combines the decision maker's perspective with the modeler's expertise—who can study the behavior and structure of the model in detail and with objectivity, and then report on it to the decision-making community. We call such third-party analysis *model assessment*.

*Model Assessment* In the electric utility field, model assessment entails the probing, scrutiny, and sensitivity testing of energy models from the point of view of how they are or could be used. It includes communication of the understanding that comes from this study in a form that is accessible to the electric power industry. As with technology assessment in general, model assessment requires going beneath the surface of the model and turning a critical eye on its application. It is not enough to know what a model says. It is important to know how it came to its conclusions, how these conclusions might be different under a change of assumptions, and why.

Consider an example. In a recent application of energy modeling, a question was asked on the effects a shift would have from continued energy growth at the historical rate to a less energy-intensive economy through a sustained program of conservation. Would it result in reduced national income? Would it cause a rise in unemployment? These questions have been hotly debated. A model to address such issues was developed by Data Resources, Inc., for the Energy Policy Project of the Ford Foundation. A conclusion drawn from the model was that an energetic conservation program would only slightly reduce real output and would substitute labor for energy.

This was not the end of the debate. In fact, publication of the results has set off a new round of controversy. Modeling applications can give rise to more questions than they answer, and they can also identify central points of disagreement. The rethinking and discussion that ensue are healthy, and therein lies the chief potential benefit of modeling. When used appropriately, formal models sharpen issues, focus debate, and shape and modify people's mental models, which, in the last analysis, guide the course of human action.

*A Program of Research* The Energy System Modeling Program plans to undertake a major effort in model assessment through its research contracts. Details will be reported in future issues of the EPRI JOURNAL. We will continue to sponsor work in the further development of modeling methodologies, as well as in the refinement, linkage, and application of a variety of energy models.

In order to discuss the issues arising from the modeling of the economic effects of energy conservation, an EPRI-sponsored conference was held in Washington, D.C., on January 29 and 30, 1976. Ideas for model assessments, as well as proposals for future research, were discussed by the participants. A report of the conference proceedings will be available later this year. *Program Manager: Martin Greenberger*

## ENERGY DEMAND AND CONSERVATION PROGRAM

### Materials Processing

Prototype models of energy usage behavior in the manufacturing sector have been developed for EPRI by Econometrica International. These results are detailed in the final report of RP433, which develops a theoretical model that will be used for forecasting energy demand by individual industries; discusses alternative specifications of functional forms in the theoretical model; and implements the model, using data for two-digit (SIC) industries.

The report begins with a discussion of the conventional theory of producer optimization. This forms the conceptual foundation for the model-building effort. Next, the discussion shows how the theory of duality can be used in the specification of the models to transform an unsolvable nonlinear problem into one that can be handled with existing numerical techniques. The last step in the theoretical process involves the specification of functional forms, focusing on recent developments in the theory of flexible functional forms as well as on the more traditional, highly structured forms.

The empirical results form the second major output of the project. The fundamental data source for the study was the *Annual Survey of Manufacturers,* published by the Bureau of the Census. Also, many data were obtained on tape from the Social and Economics Statistics Administration, Bureau of Economic Analysis, Department of Commerce. A broad class of models were estimated and tested using this data base and the conceptual framework described above. As a result of this effort, our forecasting ability in the industrial sector should be significantly improved.

The important question of how technological change in the manufacturing sector will impact energy usage patterns is an area of expanded research attention. The models produced by RP433 incorporated technological changes in the manner consistent with conventional economic theory. Research currently underway (RP682) is directed toward removing the theoretical barriers that presently limit our ability to represent technological change within the model.

Other research currently underway includes the development of models for forecasting agricultural energy consumption (RP683). Professor Laurits Christensen at the University of Wisconsin is directing this effort to construct models showing the interrelationships between the following factors of production: electricity, petroleum products, fertilizer, machinery, structures, other purchased inputs, and labor.

In addition to these current and past efforts, an interdisciplinary approach to the problem of technological change is planned for future research. This effort will involve the merger of process analysis models of various industries and the use of these models with statistical cost functions. This kind of merger will allow the use of detailed engineering judgments within a methodologically sound economic framework. *Project Manager: Larry J. Williams*

# Transmission and Distribution

John J. Dougherty, Director

This month's report describes two program areas: Overhead Lines and System Planning, Security, and Control. Next month's JOURNAL will cover DC Lines and Substations.

**OVERHEAD LINES PROGRAM**

A transmission line is usually designed by the utility and fabricated in the field. No single manufacturer produces a line; instead, many contribute their products and services. For this reason a research program on overhead transmission must include two essential elements. First, it must produce design data on conductor selection, insulation requirements, mechanical details, and line performance. These data can be used by utility design engineers to design lines that are more economical, reliable, and environmentally acceptable.

The second element of line research concerns the individual components and their assembly into the final transmission line. Research on conductors, insulators, towers, and hardware, together with research on construction tools and techniques, must be performed.

While a transmission line is a relatively simple structure, the cost implications of line design and the effects of component parts are greatly magnified by line length. It is extremely difficult and expensive to correct a problem in a line once it has been built. Reliable components and economical construction procedures must be available prior to the start of construction.

The ac portion of the overhead lines program is addressed to these specific needs. Both design information and improved components are being sought in the projects underway or planned. The program has been grouped into four subprograms to accomplish the research objectives: line design, line construction, environmental research, and line insulation.
*Program Manager: Frank Young*

**Line Design**

Projects relating to transmission line design can be divided into three categories: research relating to ultrahigh voltage (UHV) transmission, mechanical design of lines, and compact line design.

Project UHV at Pittsfield, Massachusetts, is the focal point for research on voltage levels up to 1500 kv. Work on UHV research began in 1967 with single-phase testing. In 1975 a full-scale, three-phase test line was built and energized. Three areas of research fall within the scope of this project: conductor selection, insulation requirements, and research on electric field effects.

Research related to conductor selection has been concentrated on measurements of corona loss, radio and TV influence, and audible noise. Various conductors are being evaluated in 8-, 12-, and 16-conductor bundles. Both symmetrical and asymmetrical bundles are being tested. Preliminary selection of conductor systems is accomplished through cage tests. The most promising bundle designs are then given long-term tests on the test line.

Insulation research for UHV systems has been directed principally to the study of contaminated insulator performance. In the project's contamination chamber, full-scale tests are being made on a variety of insulator units. Natural wetting of insulators installed on the test line is used as a check and calibration of procedures used in the chamber. Impulse and switching surge performance of insulators is also being investigated as part of Project UHV.

In 1975, General Electric Co., the Project UHV contractor, prepared a reference book reporting the results of the research, *Transmission Line Reference Book—345 kv and Above*. (Copies can be obtained for $25 from Fred Weidner & Son Printers, Inc., 421 Hudson Street, New York, NY 10014.)

Two aspects of the mechanical design of transmission lines are being studied in the line design subprogram: subconductor oscillations and longitudinal loading of lines.

Subconductor oscillations, or wake-induced oscillations, have resulted in failure of components on operating lines. Research conducted by Alcoa Research Laboratories has been directed toward understanding this complex phenomenon. In the early phases of the projects, monitoring equipment recorded the various modes of oscillation on actual operating lines and correlated these with wind velocity, azimuth, and terrain. Equations describing the motion for the various oscillatory modes were then derived, using a unique transfer matrix method. A final report on this project is being prepared.

Iowa State University has been studying the snap-over characteristics of bundle conductors, using model transmission lines. Stability limits have been defined. A final report is also being prepared on this work.

Transmission lines are subjected to mechanical loads that can be placed in fairly broad categories. Transverse wind, ice, and deadweight in various combinations form the primary basis for designing the transverse and vertical strengths of structures. Practice in specifying these transverse and vertical loads has been well standardized in various guidelines. In the case of longitudinal unbalanced loads, there is a much larger variation in design practice. In a project being conducted by GAI Consultants, Inc., the present practices for longitudinal unbalanced loads on transmission line structures are being reviewed. An interim report (EPRI 561, November 1975) gives a review of presently used practices. Future work is directed to the evaluation of longitudinal unbalanced loads on both rigid and flexible structures.

The final project presently in this subprogram deals with the design of compact transmission lines. Power Technologies, Inc., is using a 138-kv line as the basis for its work in studying conductor motion, radio influence, audible noise, electric field strengths, lightning performance, and reliability of very compact lines. The 138-kv test line at the Saratoga, New York, test site has a horizontal phase spacing of three feet. The results of this project will have direct application to the design of high-voltage lines for narrow rights-of-way and for uprating lower-voltage circuits to high-voltage operation. A design reference book for compact lines will be prepared in conjunction with the final report at the conclusion of the project. *Project Managers: Allan T. Johnson, Richard Kennon*

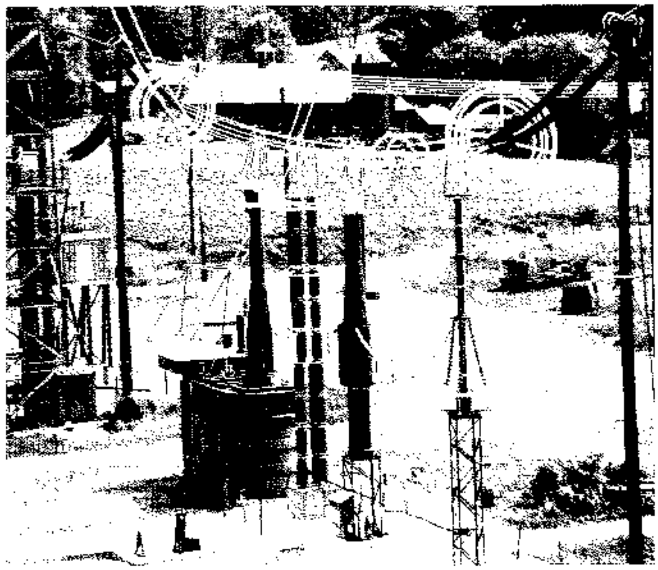
**Line Construction**

There are no projects underway in the area of transmission line construction and maintenance. This important area of research is just now being organized.

In January 1976 a seminar was held to gain insight into the problems and needs of the industry. Representatives who have nationwide experience in designing, building, and maintaining transmission lines met to discuss and recommend research projects.

Discussions were divided into five broad areas: towers and footings, maintenance, wire stringing, right-of-way and clearing, and design as it affects construction and maintenance. The participants in each discussion area had design and field experience and represented utilities, consultants, contractors, and suppliers. The results of their deliberations produced an impressive list of projects that require attention.

Figure 1 Substation at Project UHV with 1500-kv transformer, lightning arrester, and instrumentation for corona loss and radio influence voltage measurements.



Projects with the highest priority were in the area of wire-stringing technology. Research and development work, coupled with a field demonstration involving a cooperating utility, was proposed. The utility would advance its construction of a section of regularly scheduled line. This test section, perhaps 10 miles in length, would then be used as a field laboratory to investigate wire-stringing methods for 8-, 12-, and 16-conductor bundles.

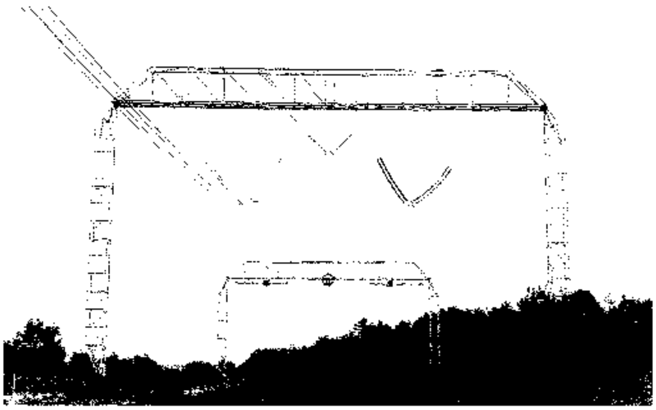
In addition, this test section of line would be used to develop tools, stringing sheaves, cable carts, hotsticks, suspension hardware, and the methods of using these devices to optimize construction and maintenance.

While the details of such an undertaking are still very much in the formative stages, the importance of such research to future UHV line construction and the potential fallout to improvements in construction methods for lower-voltage lines cannot be discounted. EPRI plans to nurture these ideas. As projects develop and as results are obtained, they will be reported to the industry.

Other areas of suggested research developed at the seminar included right-of-way management and vegetation control, foundations and anchors, fastener research, detection of broken insulators, safety evaluation techniques, grounding procedures, and improved tower design concepts. In total, approximately 30 significant ideas were gleaned from seminar participants.

A report on the seminar giving a more detailed description of suggested research projects will be available. *Project Manager: Allan Johnson*

Figure 2 Project UHV test line in a triangular configuration for testing at 1050 kv. An 8-conductor bundle using a 1.3-in conductor is shown.



**Research Related to Environmental Effects**

The environmental impact of high-voltage transmission lines has been the subject of much discussion in recent years. Research related to these effects has formed an important part of the Overhead Lines Program. Primary emphasis has been on accurately characterizing the electric fields in the vicinity of transmission lines. Engineers at Project UHV have had a principal role in this research effort.

Research at Project UHV has been in four stages. The first was the development of instrumentation for measuring fields accurately. This was followed by measurements of fields associated with the test transmission line and operating lines. Predictive techniques were then developed and checked with measurements. Finally, "field days" were held at the project so other investigators could check their methods and provide a consistent basis for reporting results of study and research.

Measurements have been made of voltages and currents induced in a variety of objects that may appear in the vicinity of a line. Research related to these effects is continuing.

Project UHV is also focused on the study of techniques for reducing the strength of electric fields at ground level. Grounded wires or energized three-phase circuits will be built under the 1500-kv test transmission line. The mitigating effects of various alternative constructions will then be evaluated.

A second project related to environmental effects of transmission lines began in 1976. Its focus is the investigation of potentials induced on gas transmission pipelines. Under the joint sponsorship of EPRI and the American Gas Association, engineers at IIT Research Institute will prepare a tutorial handbook for use by electric utility and pipeline design engineers and operators.

In addition to these projects, engineers in the Overhead Lines Program are providing close liaison with the EPRI Energy Systems, Environment, and Conservation Division on projects related to the biological effects of electric fields. Electrical aspects of experimental design, relation of fields to actual line designs, and results related to their impact on transmission facilities are reviewed. *Project Managers: Allan Johnson, Richard Kennon, Frank Young*

**Line Insulation**

The fourth subprogram within the Overhead Lines Program is line insulation. Insulation is one of the most important components of a transmission line. If a line will not hold voltage under all weather conditions, serious problems exist. The research objectives in this area relate to improving insulator mechanical and electrical strength through application of new materials, providing reliable insulations for areas of high natural or man-made contamination, understanding the fundamental physics of arc breakdown in air in order to provide more efficient insulation structures, and a continuing review of line insulation coordination criteria as they are affected by the introduction of new surge arresters, higher-speed breakers, fault limiters, and other power system changes.

Presently, two projects in progress involve the search for higher mechanical strength in porcelain insulators. I-T-E Imperial Corp. with New York State College of Ceramics at Alfred University and McGraw-Edison Co. are the contractors. *Project Manager: E. Robert Perry*

## SYSTEM PLANNING, SECURITY, AND CONTROL PROGRAM

The research program in System Planning, Security, and Control has the near-term objective of providing improved analytical methodologies in three areas: planning strategies and tools, system modeling techniques, and system control strategies. Each of these areas involves several projects that are designed to provide maximum impact in satisfying the near-term needs of the industry in bulk power system planning and operation. The satisfactory completion of these projects will provide analytical capabilities for solving new power system problems brought about by the changing growth, environmental, energy, and financial constraints of the industry.

**Program Scope**

The program is organized into the following subprograms:

- Planning—system development; planning strategies and tools; system modeling, analysis, and evaluation
- Operations—system security; system control; communications, measurement, and data
- Testing—test facilities; system and control testing
- Support Studies—theoretical studies; technology assessment

The program is addressed primarily to the analytical needs of the bulk power system planners and operators. Much of the work planned or in progress involves the development of new or improved computer methods, both for off-line analytical studies and on-line real-time control. A portion of this research is in the development of new theoretical models and techniques that show promise for power system problems. Overall, the program is one of high technology in analytical theory and methods, as opposed to programs in the physical or materials sciences.

**Program Objectives**

The principal objectives of the program over the next few years will be to provide improved strategic and simulation tools and to improve the economic control of system operation. Additional areas for emphasis are in long-range planning methodologies and system security assurance.

One of the principal strategic tools used in long-range planning is reliability methodology. Reliability methods are applied to the development of optimum generation expansion patterns to evaluate the need for network reinforcement and for the integration of generation and transmission into a reliable, operable system. The development of new and improved reliability methods for planning will be one of the principal areas of focus in the near future.

The improvement of analytical tools is another area of concentration. This includes the development of new models and simulation programs for system dynamic performance, new analytical techniques for evaluating system behavior, and improved numerical methods for optimizing computing costs and speed.

In system operations, the areas of concentrated effort will be in improved control strategies, security assurance, and economic control. The improvement in economic control concerns a broader range of fuel mixes, environmental constraints, and contractual restrictions. It also involves the theoretical concept of load management and the implementation of new methods for achieving the desired control.

In system security assessment, emphasis will be given to the creation of new techniques for determining the static effect on system operation of control or switching actions in neighboring systems. This is viewed as a first step in the development of a system equivalent that can be used to determine both static and dynamic behavior.

Research in testing will be undertaken only if additional funds are available. Testing is badly needed to determine the accuracy of the mathematical models developed for power system simulation. This need exists both for the models presently used and for new concepts and controls under study. Such a testing program requires a considerable expenditure for operating and instrumenting a sequence of tests. A program is tentatively planned, in cooperation with ERDA, for the early 1980s.

Finally, a general objective for continued theoretical research in support studies is anticipated. It is important that support be provided for the study of innovative theoretical concepts that have promise for application in power systems analysis and control. *Program Manager: Paul Anderson*

# At the Institute

## DIRECT BURNING ONLY WAY TO USE COAL FOR NOW, SAYS EPRI DIVISION DIRECTOR

Through the balance of the century, the electric utility industry will need to burn coal extensively in conventional boilers because new "clean coal" technologies can make only a small contribution, according to Richard E. Balzhiser, director of the Fossil Fuel and Advanced Systems Division.

Speaking at the 1976 Annual Meeting of the American Association for the Advancement of Science in February, the energy specialist predicted that by the year 2000 electricity could meet 50% of the country's end-use energy demands, with utility coal requirements rising to 2.4–3.6 billion tons.

Balzhiser said that for the next 25 years "coal utilization by utilities will be primarily in conventional coal-fired plants that use either scrubbers or tall stacks with supplemental control systems. Clean liquid and gaseous fuels from coal will begin to make contributions by the mid-1990s."

Richard Balzhiser, director of the EPRI Fossil Fuel and Advanced Systems Division (center), reviews some of the materials discussed at the 1976 Annual Meeting of the American Association for the Advancement of Science with Robert Seamans, head of ERDA (left), and Eric Reichl, president of Conoco Coal Development Company.

A major issue now facing the electric utilities, according to Balzhiser, is the uncertainty associated with pollution control requirements for coal use, not only for direct-fired power plants but also for coal conversion plants and power plants fueled with coal-derived fuels. Investments of billions of dollars in the next few years could be negated by the results of health effects research now underway or by capricious or politically motivated changes in regulations.

Balzhiser concluded his discussion by calling for credible, scientifically based, and economically sound emission standards so that investments in expanded mining and processing facilities, power plants, and emissions control necessary to meet the nation's energy requirements are justified. "A clear national commitment to using coal economically, while at the same time protecting the public and the environment, is necessary before coal can contribute to the achievement of our national expectations."

## Users and Developers Discuss Energy Storage Technologies

"Conventional and underground pumped hydro may account for as much as 50% of the energy storage used by electric utilities in the next 25 years," said EPRI's Joseph Pepper, relating one major conclusion of a recent conference sponsored by the Engineering Foundation. The other two conclusions impacting electric utilities were that energy storage in the form of thermal energy could improve electric utility system load factors and that dispersed storage devices may offer power system benefits in addition to those benefits attributable to centrally located storage.

The one-week conference held in Pacific Grove, California, was organized by EPRI and ERDA. It marked the first time that developers of all the energy storage technologies met with the potential users and discussed what further development is needed for successful applications, according to Pepper, project manager in EPRI's Thermal-Mechanical Energy Conversion and Storage Program.

Dr. John Peschon of Systems Control, Inc., (left) and Dr. Roosevelt Fernandes of Niagara Mohawk Power Corp. lead a discussion on dispersed storage benefits.

In addition to electric utility needs, the conference also addressed the needs of environmentalists, real estate developers, labor unions, and the industrial and transportation sector. The status of the various energy storage technologies was reviewed and the criteria these technologies would have to meet for their eventual application were discussed.

All the energy storage technologies under development, including batteries, compressed air, underground pumped hydro, flywheels, superconducting magnets, thermal, and chemical, were covered.

## Major Emphasis of EPRI Nuclear Safety Research Discussed at AIF Workshop

Results of EPRI's reactor safety program are expected to either confirm the safety margins in operating parameters and identify overly conservative controls or, in some cases, to provide a basis for improvements that further minimize uncertainties in expected performance, stated EPRI's Walter B. Loewenstein in an address given at a recent Atomic Industrial Forum on Reactor Licensing and Safety.

Loewenstein, director of the Nuclear Power Safety and Analysis Department, cited five questions on which the reactor safety program has been developed:

- What assurance is there that a minor or major off-normal incident will not occur in a nuclear plant?
- If a major or minor incident occurs, what are the realistic consequences to the public and the plant?
- Has the probability of such events occurring been reduced to the lowest practical level with current technology and can this be demonstrated?
- What design, modeling, and test features of reactor safety technology can be used to further quantify the actual safety of current and advanced systems?
- Are there any areas of concern under normal operating conditions; if so, what are their effects and how can they be quantified to establish their absolute importance?

"Most of the current activity in EPRI's nuclear safety research is devoted to assuring the safety of the light water reactor," said Loewenstein, who also stated that programs for other types of reactors are presently being formed at EPRI. The nuclear safety specialist also referred to the extensive studies being undertaken by ERDA for examining the safety of all the nuclear reactor systems and mentioned the importance of the joint ERDA–EPRI prototype LMFBR Design Project currently underway. According to Loewenstein, the results of this study will be an important factor in the continuing effort to improve reactor safety and operation.

### Fusion Examined for Producing Synthetic Fuels

A recent fusion workshop on synthetic fuels concluded that fusion energy, when available, could be used to produce synthetic fuels, such as hydrogen, methane, and methanol. Energy specialists attending the two-day workshop further identified the future direction of research and development aimed at producing fuel in fusion reactor systems.

The participants developed broad concepts of fuel-producing fusion reactors, examined the efficiency of production for specific fuels, and identified near-term (1975–1985) research needs.

"Although the main thrust of fusion development is toward the production of electricity, the utility industry is interested in alternative uses of fusion energy," said EPRI's Robert F. Scott, a project manager in the Fusion Program. "This is partly because of concern about the reliability of the advanced technology required for fusion power plants. Not only are the possibilities for producing synthetic fuels and other chemicals very promising but also they could be developed sooner than could fusion energy for electricity."

The unique nature of fusion energy produced by the "burning" of the deuterium-tritium fusion fuel permits the fuel region and the chemical-processing region to separate. According to Scott, this allows a wide variety of fusion reactor designs, including "those which would permit the production of high-quality heat, fissionable material, carbon monoxide, hydrogen, and possibly even ozone."

Fusion specialists from the U.S. and Austria discuss the research and development required for the future use of fusion to produce synthetic fuels. The workshop, managed by Fusion Systems Corporation of Rockville, Maryland, an EPRI contractor, was sponsored by the EPRI Fusion and Electrochemical Energy Conversion and Storage programs.

### Examining Possible Implications of Stricter $NO_x$ Control Standards

"If stricter $NO_x$ control standards are implemented in the future, new and critical questions on technology and cost must be answered," emphasized EPRI's Donald Teixeira, commenting on some of the main conclusions reached at a recent EPRI $NO_x$ Control Technology Seminar sponsored by the Fossil Fuel Department and attended by 135 utility, industrial, and regulatory technologists.

Teixeira said that a key conclusion of the seminar was that while staged combustion techniques have been relied on as a basis for current federal $NO_x$ standards in coal-fired boilers, their impact on boiler reliability, maintenance, and cost has not been fully resolved. Based on this conclusion, any further tightening of $NO_x$ standards on coal-fired boilers would be unsupportable from a control technology standpoint.

Teixeira, project manager for $NO_x$ control and seminar coordinator, said, "In regard to gas turbines, the only technology presently available to meet proposed EPA standards is water injection, but again, maintenance and reliability problems need considerable attention."

The $NO_x$ control specialists concluded that dry $NO_x$ control methods for gas turbines are still a long way from commercial application. "The impact of this technique on turbine performance and reliability, even at this early point in its development, is of major concern," stated Teixeira.

Another significant conclusion was that $NO_x$ generated from fuels with a high nitrogen content, such as certain coal liquids and shale oil, is probably not controllable with combustion modification approaches alone.

# Project Highlights

## EPRI Negotiates 24 Contracts

EPRI signed 24 new research contracts in January. A representative sampling of these new projects, as well as information on other current projects, follows. A list of new contracts is on page 50.

## First Consultants Named to Study Electric Utility Rates

Ebasco Services, Inc., and National Economic Research Associates (NERA) have been named as the major economic consultants for a nationwide study of electric utility rate design.

The two firms will examine five of the ten research topics defined by EPRI and the Edison Electric Institute (EEI), who are jointly sponsoring the one-year research effort.

The principal objective of the Electric Utility Rate Design Study is to evaluate peak demand pricing, that is, differential rates based on the time of use of electricity. The study was requested by the National Association of Regulatory Utility Commissioners (NARUC), a group that is seeking ways to alleviate the consumers' burden of rising fuel and electricity prices.

Ebasco is to work on electricity pricing theory, costing, and ratemaking. NERA will concentrate on these same three topics and also examine two others: demand elasticity and rate experiments.

According to Robert G. Uhler, executive director of the study, at least seven other consultants will be named to cover the remaining five topics, as well as to complement Ebasco's and NERA's efforts.

Under the direction of Joseph R. Crespo, Ebasco will develop four alternative costing methods for peak load pricing that might be used in the U.S. These will be tested, using the data of five cooperating utilities with different operating characteristics.

One utility has been chosen so far, Virginia Electric and Power Co. (Vepco). According to Uhler, Vepco was selected because of its growth in summer peak demand since 1957, its large residential customer class, its geographically varied service area, and its generation mix with a growing nuclear component. In addition, Vepco has conducted load research since 1955 and evolved summer-winter differential and off-peak rates for large industrial customers.

Under its assignment on ratemaking, Ebasco is to analyze how peak load pricing might be based on four costing methods, including the rate adjustments needed to accommodate revenue constraints and the capabilities of present-day meters. Again with task force assistance, Ebasco will translate its general rate design approaches into specific rate schedules for the five participating utilities.

Equally important, Ebasco expects to propose one or more rate schemes other than peak load pricing.

NERA's research, guided by Dr. Jules Joskow, also focuses on costing and ratemaking. The firm will develop its own approach to marginal costing within the particular circumstances of four different utilities. NERA will work closely with a task force on NERA's other main effort, the design of innovative rate forms based on these marginal costs. In connection with this, NERA will evolve a series of rate patterns that might be used by utilities in experiments with relatively small-volume customers.

NERA is also to examine the evidence on the elasticity of peak electricity demand (in kilowatts), as well as set forth NERA's considerable existing work on the elasticity of so-called average demand (in kilowatt hours).

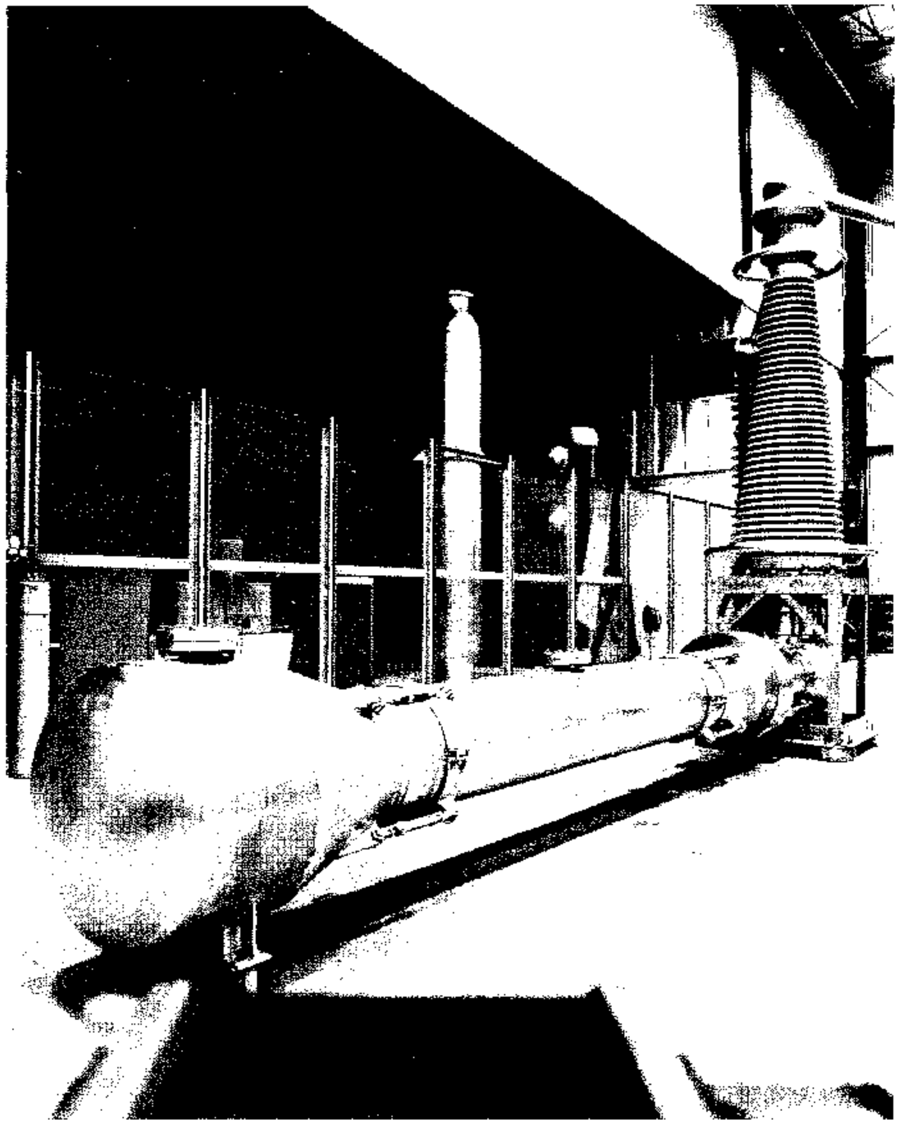
The rate design study project committee and its ten task forces, formed in 1975, were drawn from regulators, utilities (public, cooperative, and investor-owned), utility associations, and EPRI. The task forces have now begun to develop data and information. Their work will complement the consultants' efforts.

Uhler said that 29 proposals were reviewed before those of Ebasco and NERA were chosen. The decision was based, he said, on their long experience and frequent participation in regulatory hearings. Uhler also credited both firms for their thorough assessment of the rate design issues posed by EPRI and EEI and for the consultants' responsiveness to NARUC's needs.

Both consultants will submit their first reports during the spring of this year so that the project committee of the Electric Utility Rate Design Study can monitor the research and report on its progress to NARUC.

## Gas Cable Development Continues

345-kv, $SF_6$ gas-insulated cable test section similar to the test vehicle being used in a new EPRI project awarded to I-T-E Imperial Corp.



Gas cables have proved economical in very short lengths, but longer lines are not yet competitive with existing technology—except for high-power capacities of 2–3 Gva and up. At these ratings, however, the reliability of longer lines becomes a question.

"The objective of EPRI's gas cable program is to develop gas-insulated cable systems that are capable of transmitting large blocks of power, normally equivalent in magnitude to overhead systems in the EHV and UHV voltage ranges," stated Ralph Samm, program manager for Underground Transmission, in announcing an EPRI project award to I-T-E Imperial Corp. that will help achieve this objective.

According to Samm, who will manage the two-year, $455,500 study, sulfur hexafluoride (which is used in gas-insulated cables) remains stable up to 150°C, but the components of the cable, such as the conductor, encloser, and insulating spacers, cannot withstand such high temperatures. "If these components could be developed to the point where they would be reliable at 150°C, then higher power densities for a given size could be achieved," commented Samm. He added that such high-temperature, gas-insulated systems would then be more competitive over long distances with other types of transmission cables.

## A Closer Look at Radioiodine Emissions from Light Water Reactors

What contribution does radioiodine (iodine-131) released from light water reactor nuclear power plants make to the human ingestion dose from the air-grass-cow-milk food chain? This question is particularly important as it relates to costly emission control equipment that might not be necessary.

EPRI has therefore initiated a two-year, $351,000 research project with Science Applications, Inc., La Jolla, California, to find out what happens to radioiodine after it leaves nuclear power plants. Project manager for EPRI is Henry Till.

In normal LWR operation, very small amounts of radioiodine are emitted into the atmosphere. By federal requirement, however, all emissions must be as low as can be reasonably achieved technically. Essentially, this means that the dose created by such emissions and ingested by the population would be biologically insignificant.

Evidence indicates that the nature of the iodine chemical species has a significant influence on the transfer of radioiodine from air to vegetation. It is suspected that as a result of solar and other catalysts, most of the radioiodine reacts with hydrogen and carbon in the atmosphere to become methyl iodide ($CH_3I$), a relatively stable organic chemical compound with $\frac{1}{1000}$ the vegetation deposition characteristics of molecular iodine ($I_2$). If this is the case, a smaller amount of the radioiodine than is currently calculated by using mathematical models would find its way into vegetation and hence into the food cycle.

Verification of this hypothesis should result in substantial savings in equipment and maintenance costs for gas effluent treatment systems.

At least seven important factors involved in the transport of radioiodine from the nuclear power plant to the air-grass-cow-milk food chain must be studied in order to accurately assess the agricultural pathway dose. These factors are:

- The radioiodine emission from the plant to the environment (currently under study in another EPRI project)
- The chemical form of the radioiodine emission
- The atmospheric dispersion of the iodine (the subject of a recently completed EPRI state-of-the-art study)
- The deposition characteristics of the iodine
- The fraction of the deposited iodine that remains on the forage after weathering and decay
- The transfer of the iodine from the forage to the milk
- The dilution that occurs in pooling with the milk from unaffected dairy farms and the time involved in processing and distributing the milk

The specific objectives of this project are to determine the chemical forms of radioiodine being released to the environment from LWR nuclear power plants, to determine the persistence of these forms after release to the environment, and to obtain data to model the mechanisms that transfer radioiodine to vegetation. A high volumetric flow rate will be developed for this project to help determine how much of the iodine from the power plants persists as, or goes into, organic forms as opposed to other forms. The environs around four LWR nuclear power plants will be monitored, with a minimum of eight sample stations per plant. The sampling period per plant will be 20 weeks.

## Water-Cooled Gas Turbines May Offer Greater Efficiency and Power

"If water-cooled gas turbines prove to be practical for large-scale power generation, turbines could run at higher temperatures to generate more power, and at the same time, expensive fuel oil and natural gas could be saved," stated EPRI's Arthur Cohn, project manager for gas turbine studies.

Announcing a new $3.7 million project awarded to General Electric Co. for evaluating and demonstrating the best way of using water to cool rotating engine parts, Cohn said that EPRI has been sponsoring water-cooled gas turbine development since early 1974, shortly after General Electric first successfully operated a small-scale demonstrator. This award marks the third phase of EPRI's water-cooled gas turbine program at General Electric.

"For years, gas turbines have relied on fuel oil and natural gas," said Cohn. "But with skyrocketing prices and the unavailability of oil and natural gas, it became evident that methods to enable gas turbines to accommodate coal-derived fuels were sorely needed."

Today, gas turbines using air cooling cannot operate at the ultrahigh temperatures that are required for significantly improved performance without corrosion becoming a problem. With water cooling, however, high gas temperatures can be reached while turbine components get no hotter than 1000°F. At this low temperature, corrosion, deposition, and erosion can be minimized, even when such dirty fuels as residual oil or synthetic fuel from coal are used.

"Although gas turbines have been used principally by electric utilities to meet peak electricity demands," commented Cohn, "they may prove to be more useful in combined cycles for baseload and intermediate-load power." Combined-cycle power plants, using both a gas and a steam turbine, would employ the energy in the exhaust from a gas turbine to make steam to power the steam turbine. "Combined cycles can be about one-third more efficient than steam turbines alone," Cohn remarked.

EPRI's commitment to the water-cooled gas turbine program, including the new award, is over $5 million. "But," according to Cohn, "over ten times that amount is required to build a laboratory engine to prove the technology by 1981 or 1982."

A substantial portion of that funding may come from ERDA, which is currently considering General Electric's proposal as one of the contractors under the new ERDA High-Temperature Turbine Technology Program. The purpose of the government's program is similar to EPRI's objective—developing advanced-technology gas turbines for use with cheaper, coal-derived fuels. EPRI's gas turbine program is designed so it can be integrated with the government's efforts.

Information on EPRI's gas turbine program was given by EPRI's Fossil Fuel and Advanced Systems Division in the March issue of the JOURNAL.

## Nuclear Plants Designed to Withstand Tornado-Driven Debris

Nuclear power plants are designed to safely withstand the most severe postulated impacts from tornado-driven debris, according to preliminary test results by EPRI.

At Sandia Laboratories' Tonopah Test Range near Las Vegas, Nevada, a 1500-lb, 35-ft wood utility pole was driven by a rocket sled at 150 mph into a 1½-ft-thick section of a simulated nuclear power plant wall. Although the impact crushed the first 4 feet of the pole, the only damage to the wall was a slight crack on its back surface.

The utility pole test was witnessed on February 12, 1976, by 35 engineers and scientists, including 4 representatives of the Nuclear Regulatory Commission.

"Although highly unlikely, it can be postulated that debris lifted and driven by the intense winds of a tornado could create flying 'missiles'," explained George Sliter, EPRI project manager for this study. "Such flying debris could conceivably impact outer plant walls. Therefore, these concrete walls are designed to prevent penetration from flying debris, as well as fragmentation that could damage plant equipment."

The tornado-missile impacts are simulated by using rocket sleds on tracks to propel such missiles as steel pipes and wood utility poles into reinforced concrete constructed to simulate nuclear power plant walls. High-speed movies and electronic instrumentation gather information that can be used by nuclear plant designers to assure plant safety while at the same time keeping plant cost to a minimum.

"Since the tests began in November 1975, several kinds of missiles have been driven into walls at speeds up to 200 mph," said Alan Stephenson, Sandia test director. "All were stopped by the test walls." Tests have shown that such postulated missiles as reinforcing bars and pipes tend to cause more wall damage than wood poles because they deform less under impact.

"Nevertheless, we expect the test program to confirm that even the most potentially damaging pieces of debris impacting a nuclear plant during the most severe tornado that can be postulated will not compromise the safety of existing nuclear plants," emphasized Sliter.

The $215,000, one-year project is scheduled for completion by mid-1976.

### Research Seeks Better Detection and Imaging of Flaws

Under current inspection code requirements, nuclear reactor pressure vessels must have a complete volumetric nondestructive evaluation of weld regions at least once every ten years. This is now done through ultrasonic methods that detect acoustic deviations which may represent flaws. Further inspection is then required to determine the extent and nature of the flaw.

"Although the current system effectively assures the safety of pressure vessels, it is time-consuming and can result in unnecessary repair procedures," said Karl Stahlkopf, project manager for EPRI.

EPRI is now funding a $940,000 project through Battelle, Northwest Laboratories and Holosonics, Inc., for the design, fabrication, and field evaluation of an ultrasonic system for the detection and imaging of flaws in pressure vessels and piping in nuclear power plants. This will be a hybrid device, employing a focused linear array transducer that operates on a pulse echo for the highly directional purpose of finding the flaw. It then can be switched to a holographic mode for describing the flaw—its depth, size, orientation, porosity, etc.

The capability to quickly and precisely quantify an acoustic deviation discovered during a preservice or an inservice inspection could save a reactor operator considerable money. Experience has shown that different inspection teams infer different characteristics for the same defect. To compensate for uncertainty in the flaw characterization, conservative assumptions are always made for fracture analysis purposes. This compensation can often make the difference between continuing operation and a costly and time-consuming repair procedure. However, such uncertainties would be eliminated by the new system being developed.

This project is scheduled for completion in September 1977, at which time a fieldable prototype model of the acoustic (flaw) imaging system will be available.

### Nondestructive Techniques for Measuring Stress Regions

EPRI has initiated a three-year, $402,000 research project with Stanford University to develop nondestructive acoustic techniques for measuring stress regions in nuclear reactor materials that might lead to cracking.

Previous work at Stanford University's Hansen Laboratories of Physics resulted in development of ultrasonic techniques that detect defects in aircraft structures up to eighty times faster than do present methods. Now, working in conjunction with Stanford Engineering Mechanics Department, efforts will be made to adapt these techniques to the detection of stress regions in the pressure vessel walls and pipes of reactors.

The new research will focus on attaining more subtle information to see if a visual image of highly stressed regions in materials can be constructed and thus determine if they are at a point of developing cracks. "Success in this effort will result in a significant new diagnostic tool for evaluating structural integrity," according to Gary Dau, EPRI project manager.

## New Study on Plutonium Recycle Fuels for Boiling Water Reactors

A two-year, $678,000 research project to confirm the safety, economics, and performance of plutonium recycle fuel in boiling water reactors (BWRs) has been awarded to General Electric Co. Tests will be conducted in Commonwealth Edison Co.'s Quad Cities-1 facility in Cordova, Illinois.

This project is an extension of existing EPRI research (RP72-2) and should provide data to support conclusions that BWR plutonium recycle fuel can be designed to be interchangeable with uranium fuel and that its performance can be conservatively predicted.

Confirmation of the performance of this fuel, which is produced as a byproduct of light water reactor operations, would add substantially (up to 9%) to the overall fissionable resources of the country.

The scope of the tests will cover nuclear power measurements, fuel assembly and rod site examinations, and destructive fuel examinations.

Measurements of the power distribution and behavior of the plutonium-bearing fuels should confirm that:

- Plutonium-bearing assemblies will operate with power distributions that are consistent with safety constraints.
- Measured isotopic compositions result in acceptable economic values for the recycling of plutonium in BWRs.
- Plutonium recycle fuel assemblies of the island design can be used interchangeably with uranium fuel assemblies in BWRs.
- Overall assembly and rod performance characteristics of plutonium recycle fuel are essentially identical to those of $UO_2$ fuel.

The goal is a fully focused development program that covers significant aspects of the steady state performance characteristics of plutonium recycle fuel. The EPRI project manager is Burt Zolotar.

A BWR fuel bundle is lifted from its storage area beneath 15 feet of water for inspection at Commonwealth Edison Co.'s Quad Cities-1 facility in Cordova, Illinois. The inspection is part of a series of EPRI studies, which indicate at this time that BWR recycled plutonium fuel can be designed to be interchangeable with uranium fuel. Visible on the right are additional storage racks (numbered) where the spent and/or used fuel is kept cool.

## New Contracts

| No. | Title | Duration | Funding ($000) | Contractor |
|---|---|---|---|---|
| **Fossil Fuel and Advanced Systems Division** | | | | |
| RP226-2 | Development of Zinc-Chlorine Battery for Load Leveling | 1 year | 1088.0 | Gulf & Western Industries, Inc. |
| RP234-3 | Ultrahigh Temperature Turbine Program | 2 years | 3727.0 | General Electric Co. |
| RP237-3 | Conceptual Reactor Design Studies of Laser-Initiated Inertial Confinement Fusion | 30 months | 1000.0 | University of Wisconsin |
| RP538-1 | Preparation of Data Book on High-Temperature Oxidation and Corrosion of Metals and Alloys in Electrical Generating Systems | 11 months | 18.0 | Battelle, Columbus Labs. |
| RP553-1 | Solar Heating and Cooling of Buildings Requirements Definition and Impact Analysis | 1 year | 690.0 | Aerospace Corp. |
| RP633-1 | Vapor Pressures, Viscosities, and Volumetric Behavior of Coal-Derived Products | 3 years | 327.0 | William Marsh Rice University |
| RP645-3 | Advanced Fueled Reactors: Overall Synthesis and Design Tasks | 26 months | 200.0 | Brookhaven National Lab. |
| RP648-1 | Requirements Definition and Impact Analysis of Solar-Thermal Power Plants | 20 months | 539.8 | Westinghouse Electric Corp. |
| RP653-1 | Brine Chemistry and Combined Heat/Mass Transfer | 16 months | 450.0 | Battelle, Pacific Northwest Labs. |
| RP729-1 | Economic Assessment of Utilization of Fuel Cells in Electric Utility Systems | 7 months | 172.3 | Public Service Electric & Gas Co. |
| RP731-1 | Engineering Design and Cost Analysis of Chlorine Storage Concepts for Zinc-Chlorine Load-Leveling Battery | 6 months | 82.6 | Bechtel Corp. |
| RP739-1 | Preliminary System Analysis of a Solar Power Station | 8 months | 50.0 | General Atomic Co. |
| **Nuclear Power Division** | | | | |
| RP227-2 | Multidimensional Transient Analysis Code for Reactor Safety Studies | 17 months | 6.0 | Massachusetts Institute of Technology |
| RP308-2 | Model to Bound Impact Characteristics of Tornado-Propelled Objects | 8 months | 170.7 | National Aeronautics and Space Administration |
| RP600-1 | LWR Environmental Radioiodine Chemical Species Measurements | 2 years | 351.0 | Science Applications, Inc. |
| RP688-1 | Investigation of Transition Boiling | 17 months | 20.0 | University of Cincinnati |
| RP705-1 | Development and Maintenance of a Nuclear Experience Data Base | 1 year | 149.8 | Science Applications, Inc. |
| **Transmission and Distribution Division** | | | | |
| RP655-1 | EHV Reactor Capacitor Switch | 2 years | 513.8 | Westinghouse Electric Corp. |
| RP661 | Development of Distribution and Subtransmission $SF_6$ Circuit Breaker and Hybrid Transmission Breaker | 17 months | 883.1 | I-T-E Imperial Corp. |
| RP672-1 | Superconductors in Large Synchronous Machines | 11 months | 117.0 | Massachusetts Institute of Technology |
| RP747-1 | Investigation and Status Report on Concentric Neutral Corrosion of URD Extruded Cable | 7 months | 47.8 | Harco Corp. |
| **Energy Systems, Environment, and Conservation Division** | | | | |
| RP674-1 | Analysis of Airborne Polycyclic Organic Matter | 18 months | 209.0 | Oregon Graduate Center |
| RP683-1 | Energy-Conserving Technological Change in Forecasting Manufacturing Usage | 6 months | 97.0 | Economics Research Group Ltd. |
| RP759-2 | Fuel and Energy Price Forecasts | 8 months | 98.6 | Foster Associates, Inc. |

# New Publications

Each month the JOURNAL publishes summaries of EPRI's most recent reports. Supporting member utilities receive copies of reports in program areas of their designated choice. Supporting member utilities may order additional copies from EPRI Records and Reports Center, P.O. Box 10412, Palo Alto, CA 94303. Reports are publicly available from the National Technical Information Service, P.O. Box 1553, Springfield, VA 22151.

### Fossil Fuel and Advanced Systems

EPRI 316-1 MOLECULAR PROFILE ANALYSIS OF COAL PRODUCTS
*Final Report*
This is the first annual progress report from the Mass Spectrometry Research Center of Stanford Research Institute on its research program "Field Ionization Molecular Profile Analysis for Coal Research." The objectives of the program are to develop instrumentation and experimental methodologies for characterizing coal liquefaction products by mass spectrometric techniques.

The problems in obtaining low-cost crude oil have focused on coal as a much more attractive source of liquid fuel. However, the characterization of liquefaction products is very difficult; the products are complex mixtures of organic compounds that have a wide range of molecular weights. Modern field ionization mass spectrometry can produce molecular weight profiles of complex mixtures without preliminary fractionation.

The research program has tested and confirmed the feasibility of this mass spectrometry analysis and is now adapting a 90°, 25-cm-radius sector magnet to cope with the special requirements of coal liquefaction product analysis. It is also adapting a field ionization source (developed in another research project) to analyze the nonvolatile products of coal liquefaction. The project has also developed computerized data-handling techniques to generate noise-free spectra. *Stanford Research Institute*

### Nuclear Power

EPRI 217-2-5 USER'S GUIDE FOR THE WAM-BAM COMPUTER CODES
*Key Phase Report*
This report contains the information needed to use the WAM-BAM computer codes, which were developed to make probabilistic evaluations of systems modeled with Boolean algebra. The models can take the form of event trees, fault trees, or simply a Boolean expression. The basic difference between these codes and others is that they allow all Boolean operations, thus allowing modeling of "NOT" conditions and dependent components. The current version calculates point estimate probabilities for the events of interest in the system from point estimates of the component's unavailability (or availability). *Science Applications, Inc.*

EPRI 232-2 FRACTURE TOUGHNESS OF FERRITIC MATERIALS IN LIGHT WATER NUCLEAR REACTOR VESSELS
*Final Report*
Fracture mechanics has been integrated into the construction, operation, and inspection of nuclear pressure vessels since the Summer 1972 Addenda to the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. One critical element of fracture mechanics analysis is the accurate measurement of fracture toughness. The code reference toughness data for nuclear materials were generated by the Heavy Section Steel Technology (HSST) Program. These data were correlated into a reference curve, the $K_{1R}$ curve, by the Pressure Vessel Research Committee (PVRC) Ad Hoc Group on Toughness Requirements.

In order to corroborate the HSST data, a PVRC/Metal Properties Council Task Group developed a recommended research program eventually sponsored by EPRI. This report describes one program conducted for EPRI by the Power Systems Division of Combustion Engineering. The materials examined represent five production heats of SA533 Grade B, Class 1 plate, four automatic submerged arc weldments, four manual shielded metal arc weldments, and two heat-affected zones. The appendixes contain pertinent test data.

The report lists several major goals of the program and the results of the examinations. It also makes the following recommendations for future research: The reproducibility and resolution of the drop weight NDTT should be improved; the analysis of the instrumented, precracked Charpy Test may need to be improved; and a reliable means for the detection of subcritical crack growth should be developed. *Combustion Engineering, Inc.*

EPRI SR-26-R USE OF NUCLEAR PLANT OPERATING EXPERIENCE TO GUIDE PRODUCTIVITY IMPROVEMENT PROGRAMS
*Special Report*
Nuclear generation units now supply more than 8% of the nation's electric energy needs at operating costs often below those of fossil-fuel-fired units. However, even with this cost advantage, there are still many reasons for improving the performance of nuclear units, including conservation of fossil fuel, reduction in national and local fuel costs, and improved utility flexibility in meeting load demand at lowest operating costs.

This report examines the productivity of existing light water reactor capacity and shows how it can be increased. However, it is concerned not only with identifying useful improvement activities but also with selecting high payoff areas based on need, probability, time factors, and participants. The emphasis is on a quantitative approach to selection methodology, which derives from a critical review of nuclear unit operating experience.

EPRI SR-28 CONFERENCE PROCEEDINGS: POWER PLANT OPERATOR SELECTION METHODS
*Special Report*

This report of the Power Plant Operator Selection Methods workshop provides a survey of current practices and problems in the area of selection testing. The workshop was held by EPRI at Palo Alto, California, on June 2 and 3, 1975. The 80 or so participants, most of whom represented utilities, are involved in the selection, training, and supervision of power plant operators.

Information was exchanged on selection testing experiences, especially as they relate to guidelines from the Equal Employment Opportunity Commission, the Nuclear Regulatory Commission, and industry standards. Testing services for personnel selection in power plant operation programs were described. Research needs for improved operator selection methods were also discussed, with emphasis on programs suitable for EPRI support.

**Energy Systems, Environment, and Conservation**

EPRI 262 SULFUR DIOXIDE INTERFERENCES IN THE MEASUREMENT OF AMBIENT PARTICULATE SULFATES
*Final Report, Volume I*

The major objective of the program was to establish quantitatively the extent to which sulfur dioxide is converted to sulfate during high-volume (Hi-Vol) particulate sampling employing glass-fiber filters. A secondary goal was to determine the amount of interference that sorbed, but unoxidized, $SO_2$ has on the sulfate analytical method. A significant part of sulfate measured by the Hi-Vol filter techniques may be an artifact resulting from conversion of $SO_2$. Further, the contamination is a strong function of the weather at the sampling site. The report summarizes the experimental techniques employed and the results of the study, and the appendixes contain extensive documentation of all data. *Radian Corp.*

EPRI 335-1 ECONOMIC ANALYSIS OF COAL SUPPLY: AN ASSESSMENT OF EXISTING STUDIES
*Final Report, Volume I*

EPRI's Energy Supply Program is making an extensive effort to better define and estimate the future role of coal and coal technologies. In order to provide a basis for future research and to avoid duplication, a review of recent and ongoing work by others seems prudent. To this end EPRI contracted Pennsylvania State University to survey and evaluate recently completed coal supply studies and meet with the people currently conducting them. The first report of reviews and critiques was published in May 1975 (RP335, Key Phase Report). This second report continues by reviewing ten studies in detail and commenting on seven others. Together, the two reports offer a good picture of the current state of coal supply analysis and should be of major interest in utility planning. *Pennsylvania State University*

**Transmission and Distribution**

EPRI 325A DISTRIBUTION TRANSFORMER TANK PRESSURE STUDY
*Final Report and Appendix*

Calculated static pressures may occur within faulted oil-filled distribution transformers as a result of arcing and gas generation under known conditions (such as air space, specific fuses, and specific pressure relief devices) and also under unknown conditions (such as actual fault current, arc length, arc location, and gas temperatures). Tables show calculated pressures for a wide range of transformer air spaces, a selection of pressure relief devices, and a wide range and variety of circuit-protecting fuses. In each case the calculation of pressure covers a full range of fault currents; most protective fusing used for overhead, pad-mounted, or submersible distribution transformers is included in these tables.

The tables guide the utility engineer in formulating operating procedures, in estimating the magnitude of required transformer tank strength, and in evaluating the effectiveness and noneffectiveness of pressure relief devices. They also provide direction in reviewing fusing practices, in pinpointing distribution system locations requiring special attention, and in assuring proper coordination between fusing, available fault current, and transformer mechanical reliability.

Even though impact-type forces are not considered, the pressure tables can aid in the design of distribution transformer enclosures either by the retrofitting of existing transformers with automatic pressure relief devices or by the modification of fusing practices for distribution transformers.

This report also provides helpful information for those preparing specifications and standards for all types of oil-filled distribution transformers. *Allis-Chalmers Corp.*

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