Gaseous Fuel From Coal

ELECTRIC POWER RESEARCH INSTITUTE

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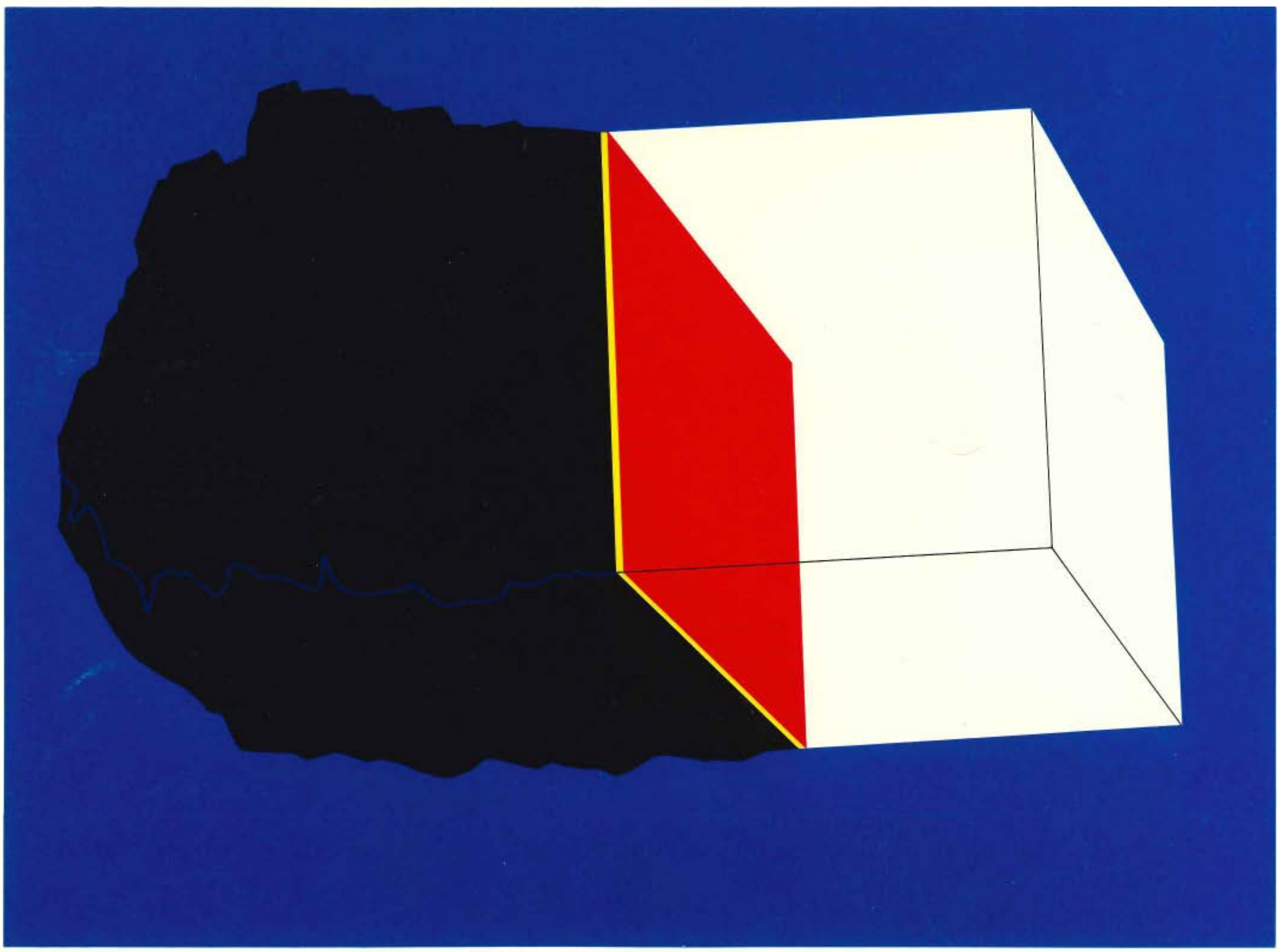

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EPRI JOURNAL Staff and Contributors
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Graphics Consultant: Frank A. Rodriquez

Robert A. Sandberg, Director
Ray Schuster, Assistant Director
Communications Division



Address correspondence to:
Editor
EPRI JOURNAL
Electric Power Research Institute
P.O. Box 10412
Palo Alto, California 94303

Cover: A thin red zone of combustion triggers the complex of oxidation reactions that convert raw coal to clean, gaseous fuel for tomorrow's electric power generation.

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## Editorial



## Features



## Departments



## Technical Review

# Coal Gasification: Who Needs It?

Electric utilities have an important opportunity right now that will yield a new baseload power option, proved at commercial scale, in as few as seven years. This opportunity flows from a remarkable convergence of federal policy, commercial strategy, and technology development.

The policy is the U.S. resolve to do three things: reduce oil imports, restrict oil and natural gas to their highest-priority uses, and cut the environmental pollution from all energy systems. The Power Plant and Industrial Fuel Use Act of 1978 most recently expresses this resolve in its schedules for electric utilities and many other industries to shift from oil and natural gas to coal. The purposes of the National Environmental Policy Act of 1969, administered through EPA, are already familiar.

The increasingly evident commercial strategy is the desire of energy companies to finance, prove, and adopt coal gasification. For oil refiners and petrochemical firms, synthetic gas is a feedstock for hydrogen and chemicals, as well as a fuel to replace natural gas. For companies with coal holdings, gasification processes and products are an attractive package for serving energy markets in compliance with federal policy.

The technology development is twofold. One element is the advent of second-generation technology for coal gasification that is cleaner and more efficient and that operates at higher unit capacity than any now in commercial use. An even more important element is the functional integration of gasifiers and power-generating units—especially combined cycles of combustion and steam turbines. These should be able to produce electricity at costs directly competitive with coal-fired units equipped with flue gas scrubbers, as well as comply with the severe pollution control standards projected for the mid-1980s. They should also afford distinct reductions in cooling-water requirements and yield marketable solid sulfur in place of waste sludge.

Coal gasification is naturally of paramount interest to a specialist in the technology. And understanding its fundamentals is the basis for establishing its potential as a power fuel source. The first article in this issue of the *EPRI Journal* supplies that foundation. But the paramount interest of a utility executive is to supply electricity at the lowest unit cost. EPRI's technical program staff has had to recognize both viewpoints during four years of sponsored study, assessment, and development of gasification processes that lend themselves to utility use. Our basic conclusion is that the variations in cost among second-generation gasifiers are relatively minor in their effect on the busbar cost of electricity.

What is important is the status of second-generation technology and the readiness of its developers to cooperate with the electric utility industry in bringing it to operational reality. Several gasification methods today represent inventions at a mature status: modular trains of high unit capacity for fuel gas production. Suppliers of gasifiers and processes and suppliers of generating units are now at the point where their equipment can be blended into a system for electric power generation. Importantly, this can be done with combustion turbines that are substantially ''off the shelf''—that is, designed for inlet temperatures of about 1100°C (2000°F).

Most aspects of coal-gasification–combined-cycle systems have been thoroughly analyzed. However, U.S. utilities have no experience in operating such systems to supply electricity under authentic demand conditions. The all-important unknowns are the system control aspects for reliable integration into the overall utility system. Engineering and system experience is therefore crucial to completing the technology evaluation.

Utilities are not alone in pressing for better coal gasification technology. Worldwide there are at least 50 commercial plants producing gaseous fuels and feedstocks for industrial markets, but these are using first-generation technology. Also, an established data base from relatively large-scale, second-generation installations exists. It is time for a joint effort to complete the development of coal gasification systems for power generation.

The next step is now pending. EPRI, Southern California Edison Co., and Texaco, Inc., are expected to be the first of several sponsors of a 100-MW integrated gasification–combined-cycle plant to be built and operated on the Southern California Edison system near Barstow within the next five years. Performance of that plant should establish whether electric utilities can use coal gasification, why, and how.

Seymour B. Alpert

Seymour B. Alpert
Technical Director for Fuels
Advanced Fossil Power Systems Department
Fossil Fuel and Advanced Systems Division

# Authors and Articles

From a ragged pile of coal to an orderly wave of alternating current is a long but familiar transition in the conversion of fuel to electric energy. But "Coal Gasification for Electric Utilities" (page 6) adds a step that is not so familiar: conversion of lumps of dirty coal into a stream of uniformly clean combustible gas. It's not alchemy, and it needs to be understood if we are to appreciate the logic and potential economy of synthetic-gas-fueled power plants.

In reviewing the fundamental process and today's major technological approaches, one point becomes especially clear—utility gasification developments are prompted, above all, by environmental needs and standards. Not only is the product fuel clean burning in comparison with any grade of raw coal but gasifiers can now be operated without releasing deleterious by-products or emissions.

To develop the article, *Journal* feature editor Ralph Whitaker was guided by Neville Holt and Michael Gluckman of the Advanced Fossil Power Systems Department of EPRI's Fossil Fuel and Advanced Systems Division. Holt, who was appointed manager of the Clean Gaseous Fuels Program in June 1974, has gradually directed EPRI's work away from gasification processes alone and toward integrated generating systems based on various synthetic fuels. During 10 earlier years, he worked with C. F. Braun & Co. and with Cities Service Co., where he became manager of synthetic fuels. Holt holds a BS and an MA in chemistry from Cambridge University.

Gluckman heads his department's Engineering and Economic Evaluation Program. An associate professor of chemical engineering at City College of the City University of New York before joining EPRI in September 1975, he had previously worked as a process engineer in the paper industry while earning his PhD at CUNY. Earlier, Gluckman graduated from the University of Cape Town in South Africa.

■

Energy is stored on every electricity generating system in the form of power plant fuel. But virtually none is stored beyond the turbine-generator coupling. This is frustrating. Storing power plant output would open new avenues of economy in generating capacity requirements and in the mix of plant types needed for around-the-clock and peak-period operation, and therefore in the use of the cheapest, most available fuels.

So far, only hydroelectric facilities fill the bill. High-head dams store cheap fuel that would otherwise be totally lost, and pumped-storage reservoirs use off-peak power to build hydroelectric heads that can be tapped during peak periods. But both are strikingly site-specific.

"Eighty Atmospheres in Reserve" (page 14) develops the case for energy storage on a much wider basis, using air as the medium and underground geologic features as the reservoirs. But geologic criteria are only part of the assessment reviewed by Nadine Lihach, feature writer for the *Journal.* Aided by three of EPRI's technical staff, Thomas Schneider, William Stevens, and Antonio Ferreira, she also covers engineering problems of cyclic reservoir operation and the equipment and fuel developments needed for compressed-air storage to be feasible.

Schneider has managed EPRI's Energy Storage Program for the Energy Management and Utilization Technology Department since January 1977; Stevens and Ferreira are two of his project managers. Schneider is a physicist (1971 PhD from the University of Pennsylvania), whose four earlier career years were with New Jersey's Public Service Electric and Gas Co., where he recommended and directed R&D projects and assessments in many energy conversion and storage technologies—batteries, electric vehicles, fission, and fusion.

Stevens (1968 BS in mechanical engineering from Purdue University) came to EPRI in October 1978 on loan from the research and engineering operation of Bechtel National, Inc. and earlier was with Bechtel Power Corp. He has moved through coal-fired power plant design; field construction, startup, and operation; and feasibility studies on advanced energy conversion and storage concepts. His specialties are thermal and mechanical techniques, such as compressed air, underground pumped hydro, and sensible heat media.

Ferreira (1950 BS in civil engineering from the University of Massachusetts) is also on loan; he came to EPRI in 1977 from Northeast Utilities Service Co., where he is hydroelectric consultant and was formerly chief hydraulic engineer. Ferreira held key responsibility for the construction and early operation of the 1000-MW Northfield Mountain plant in Massachusetts, the first U.S. utility project to employ an underground powerhouse in conjunction with pumped storage.

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Energy R&D incorporates values that go beyond technical substance and sometimes even beyond experimental methodology. The management approach has its own logic, and the way in which research participants interact can produce lessons for the conduct of work in totally different disciplines.

"Management Approach to High-Risk Research" (page 19) is thus much more than a review of thermophotovoltaic device performance that has progressed from 7% efficiency to 26% and is now heading for 35%. And it's more than the evolution of a single, tentative $85,000 project into a $400,000 multiproject effort today.

Feature writer Jenny Hopkinson portrays this context in terms of the interplay between a researcher, Stanford University's Richard Swanson, and a project manager, EPRI's Edgar DeMeo, as the project has expanded to take in other contractors, additional Solar Program staff, and several EPRI consultants and utility advisors.

DeMeo has been responsible for EPRI's photovoltaics research since he joined the New Energy Resources Department in August 1976. He is a 1963 graduate in electrical engineering from Rensselaer Polytechnic Institute, who later earned MS (1965) and PhD (1968) degrees at Brown University. DeMeo taught at the U.S. Naval Academy for two years and at Brown for seven; at the same time, he did research and was a consultant in his special field, solid-state materials.

■

While three or four years in the early life of an R&D effort provide one kind of insight into research management, one day of concentrated seminar proceedings at a later stage provides another. In "New Controls for Reactive Power" (page 30), John Marks lays out the capabilities and trade-offs that utilities must consider as they evaluate and implement new technology for faster, smoother VAR switching.

Marks, who is technical information coordinator for EPRI's Electrical Systems Division, attended the conference that serves as the setting for this technical review. An old hand at reporting and interpreting power system developments, Marks was an *Electric Light & Power* editor for nine years before joining EPRI in March 1974.


Gluckman


Holt


Stevens Schneider


Ferreira


DeMeo


Marks

# Coal Gasification for Electric Utilities

**Improvements in process technology have made gasification both cleaner and more efficient at higher coal capacity. Economical utility power systems that link gasifiers with generating units are now in sight.**

Coal gasification as a source of fuel for power generation is old practice. Inefficient and dirty gasification plants were operated in Europe before the turn of the twentieth century, and their gas generated electric power in primitive engines. In the 1930s low-cost German brown coal was processed in the newly invented fluidized bed, a more efficient means to synthesize gaseous fuel for power generation.

But the older practice of raw coal combustion remained reliable throughout those years, and coal-fired boilers were successfully scaled up in size and efficiency. Oil and natural gas also became increasingly cheap and available throughout the world, so coal gasification was shelved as a fuel technology for power generation.

Circumstances are different today. Coal combustion has become much more costly, especially in the United States, with the advent of environmental standards for air and water quality and for the handling of fossil-fired power plant waste. Oil and natural gas supplies have become uncertain and costly because of scarcity or economic regulation. Coal gasification therefore warrants a new appraisal from the electric utility perspective.

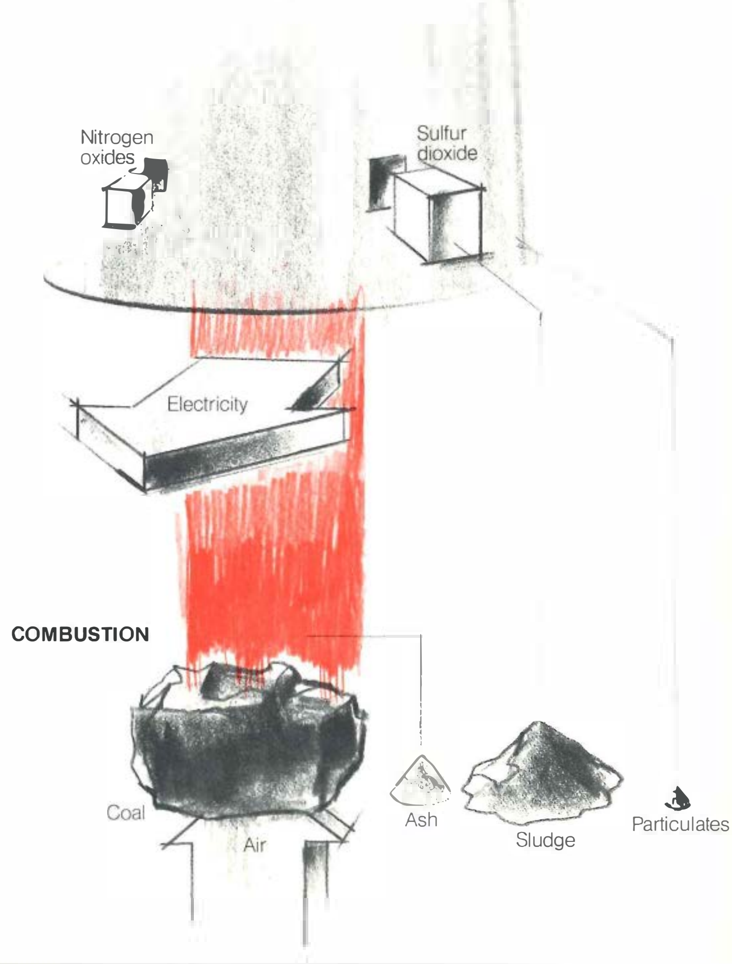
Two aspects of gasification are important. One is the technology of the process itself. The other is the technological system for applying it economi-

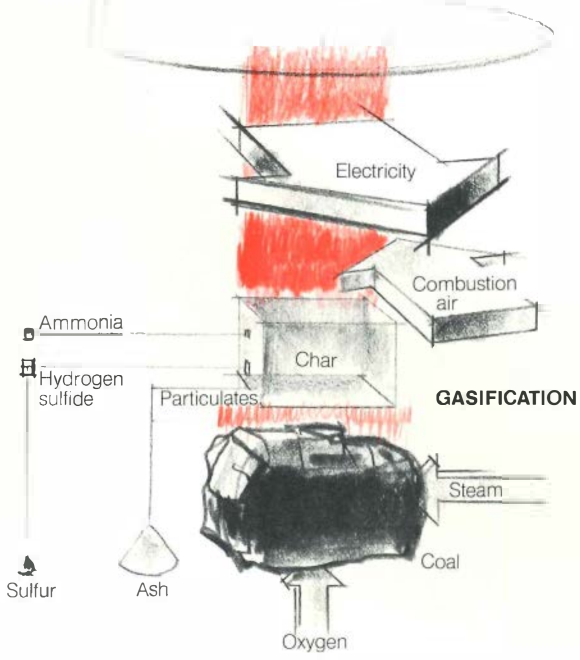
The environmental benefit of coal gasification is apparent in this comparison of atmospheric combustion at 103 kPa (15 psi) and entrained gasification at 4137 kPa (600 psi). The latter schematic includes subsequent combustion.

Relative *volumes* of oxidant, steam, gases, and waste products are shown for systems of approximately equal generation capacity.

The key feature of gasification is its progressive conversion of coal to char and then to gas, involving reactions that are controlled to permit selective removal of desired and undesired products along separate paths.

The pressurized gasification process involves less structure (hence material and site economy), but most important, it requires a lesser volume of initial oxidant (pure oxygen rather than air in this example). The volume of gas from which potential pollutants are removed (as hydrogen sulfide and ammonia) is thereby much smaller, as is the extraction equipment required. A major related advantage is the absence of scrubber sludge waste. Finally, the product gas going into combustion is clean.






cally and reliably on utility systems. To appreciate the latter, it is useful to distinguish gasification from combustion, to summarize the variety of chemical reactions and products that can evolve from different coals and process conditions, and to trace the technological approaches that are now in their second generation and satisfy the dual need for a clean process and a clean fuel.

**Gasification versus combustion**

The significant constituents of coal and air are carbon and oxygen. Their oxidation reactions yield gases. The most familiar reactions are those of combustion, which is virtually complete oxidation, yielding noncombustible gases. These reactions are exothermic—they produce heat, and that is their obvious and traditional use. Raw coal has been a main source of domestic and industrial heat for centuries, and even today it is an important boiler fuel for raising steam to drive electric utility turbine generators.

There are partial oxidation reactions, too. These are largely endothermic—they consume heat. But more to the point, they yield gases that are combustible. The most rudimentary coal gasification process was devised late in the eighteenth century. This was destructive distillation (pyrolysis), chemical changes induced by heat in the absence of air. Volatile methane ($CH_4$) and other combustible gases were thereby created and became the basis of a gas light industry that flourished for over 100 years. The convenience, economy, and performance of gas illumination were superseded only by electricity, and the familiar city gas works in the United States thereafter competed only in the production of industrial fuel.

What controls or differentiates the occurrence of these oxidation reactions?

The basic chemistry for either combustion or gasification is mainly a function of time, temperature, and oxidant-to-fuel ratio. Boilers and gasifiers are therefore designed for distinctively different combinations of these conditions.

At issue in utility gasification development today are the efficient use of resources (water and land, as well as coal itself), competitive capital and power production costs, and (cutting across all the candidate processes) environmental benefit. With the troublesome coal constituents removed before combustion, power systems that burn gaseous fuels can meet stringent emission standards for oxides of sulfur and nitrogen and particulate matter.

### Products of gasification

In all gasification reactors the major design consideration is the means for bringing coal and either air or oxygen into intimate contact and controlling the elemental carbon-oxygen reactions. Geometry is important—the flow paths of coal, oxidant, steam, and liquid and gaseous products. But the production of gas is not as simple and orderly as it appears.

Coal is a complex and highly variable substance, the product of vegetation in many past geologic eras that was fossilized under heat and pressure in the presence of many chemicals. Coal from different geologic formations contains different proportions of carbon and of potentially gaseous hydrogen, oxygen, sulfur, and nitrogen. There are also large amounts of silica and alumina, plus traces of many other elements.

In a coal gasifier, volatilization first produces methane and several other combustible gases. Chemical reactions of carbon with oxygen and steam then yield the major products, carbon monoxide (CO) and hydrogen ($H_2$).

The sulfur reaction in a gasifier is especially significant. Since sulfur is chemically reduced to hydrogen sulfide ($H_2S$), which is easily separated in a later cleanup of the gas stream, synthetic gas emerges as a clean-burning fuel. There is no sulfur remaining to form the familiar pollutant, sulfur dioxide ($SO_2$), that is generated in raw coal combustion. Nitrogen leaves the reactor either in molecular form or as water-soluble ammonia ($NH_3$).

Ash is no small concern. Typically composed of silica, alumina, and lead and iron oxides, it usually amounts to 5–35% of coal content. It is corrosive when hot, and it is the major material-handling problem in either combustion boilers or gasification reactors. Expertise in ash handling is thus a major point of competence among manufacturers of such equipment.

Finally, there are tars (complex and often toxic heavy hydrocarbons) that form under certain reactor conditions in various amounts. Liquid at best, sticky at worst, they are reactive and may also be a mechanical impediment by clogging apparatus, plugging a coal bed, and coating suspended particles so that they agglomerate into an unmanageable mass. Process developments today seek to avoid tar formation or to provide a means for the tar to be consumed.

### Three process approaches

Today's gasification developments are a catch-up effort. The technology languished when oil and clean natural gas became cheaper. Special circumstances in oil-poor nations have been the exception; for example, Germany during World War II and the Republic of South Africa today.

Three process approaches—plus a variant of one of them—illustrate gasification chemistry, reveal the problems of handling various reactants, and point up the distinctive effects of different coal properties. One approach is the fixed-bed gasifier, which is operated at temperatures that maintain the residual ash in solid form. A variant allows the ash to become molten slag. The fluidized bed is a second approach, and the entrained system is a third. These three were conceived in chronological order, and to some extent each is a solution to the problems created (or left unresolved) by its predecessor. Even so, the needs of different nations and industries have brought about their independent refinement and commercial use.

### The fixed-bed gasifier

Most simply, the fixed-bed gasifier is a vertical cylinder into which the crushed coal is fed from above. The coal lies on a grate through which the oxidant is introduced from below. It is thus a countercurrent system: gas flows upward through the bed and the residual ash gradually settles downward, falling through the grate into a disposal hopper. In essence, the coal particles do not move with respect to one another; there is no aerodynamic mixing (the oxidant velocity is controlled to prevent it), but each particle of coal is constantly contacted by a fresh supply of oxidant or product gas.

The closely controlled temperature profile in this reactor governs the phenomena and reactions throughout the bed. Combustion occurs at the bottom, sustained by the oxidant and hot char directly above the grate. The combustion temperature should not exceed 2100°F (1150°C), a typical ash fusion point, and this is ensured by the injection of large amounts of steam as a coolant, along with the oxidant.

Above the combustion zone, the temperature level progessively falls to about 1400°F (750°C) as the steam, oxidant, and combustion gases proceed upward, heating the coal and reacting endothermically with it. This is the gasification zone, yielding carbon monoxide and hydrogen. Near the top of the bed the reactions cease; in this zone—about 600–1000°F (300–550°C)—volatile products are driven off the cold, fresh coal that is falling into the bed.

### Practical limitations

The fixed-bed gasifier, particularly the 40-year-old German Lurgi technology, is proved and commercially available. This is its main advantage. But it has prob-

Coal gasification must be a clean process yielding a clean fuel. Second-generation process technology today satisfies much of that need.

Coal gasification must also be applied in an economical manner if it is to compete successfully with raw coal combustion (including scrubbers, of course) in utility service. In particular, gasification must be incorporated into a fuel- and power-production system that is reliable for serving baseload demand. Such a system, however, has to be more than a serial combination of gasifier and generating unit. The independent efficiency or economy of either machine alone is misleading.

EPRI has evaluated several decoupled systems, all of them based on coal gasification products suitable for combined-cycle power plants. For example, intermediate-Btu gas delivered over relatively short distances ranges from \$3.50–\$5.00 per million Btu (mid-1976 costs), yielding an overall efficiency of about 28%, coal to busbar (heat rate 12,000 Btu/kWh). For methanol, the comparable figures are \$6–\$8 and 22% (15,500 Btu/kWh); and SNG figures are estimated to be in the same range.

The choice of gasification process is not the determinant in any of these examples. And because of their high fuel cost, none would compete with direct-fired coal for baseload duty; at best they might be considered for intermediate or peaking service. In short, simply producing synthetic gas and piping it, even just over the fence, to a power plant is not enough.

Baseload economy comes from overall system efficiencies that are realized only by functional integration of gasifier and generator. Moreover, the determining factor for equipment selection is the state of development and the reliability of both.

Among second-generation gasifiers, the Texaco single-stage entrained system appears particularly promising today. A technology for the partial oxidation of heavy oils, it is in use at 74 commercial plants around the world. It has been adapted to coal gasification at 15-t/d pilot scale in California during the past four years and at 150 t/d in Germany for over a year.

Among combustion turbines, any of several commercially available units is suitable, using nominal inlet temperatures of 2000°F (1100°C). Advanced designs at 2600°F (1400°C) are not required.

Information recently developed for EPRI by General Electric Co., United Technologies Corp., and Westinghouse Electric Corp. shows that Texaco-based combined-cycle systems using today's combustion turbines can be configured to yield a system efficiency of 37–39%, coal to busbar (heat rate 9200–8750 Btu/kWh). Functional integration principally includes interchange of steam and boiler feedwater between gasification and generating equipment, and this suggests the shared or linked operation of many plant utilities and auxiliary systems. Working power plants of, say, 1000-MW capacity are seen to be modular—many parallel trains and from 5 to 10 combustion turbines—and therefore have a low possibility of total forced outage.

Performance and cost estimates indicate that a 1000-MW Texaco-based plant should be competitive with a pulverized-coal-fired plant that meets the New Source Performance Standards proposed by EPA in 1978. A coal-fired plant typically operates at about 34–36% overall efficiency (10,000–9500 Btu/kWh). If emission standards are further tightened, then gasification–combined-cycle plants should become increasingly attractive, because sulfur and nitrogen controls are more a function of system operation than of equipment design.

During gasification, most of the sulfur in the coal is converted to hydrogen sulfide, which can be removed to the desired extent by any of several commercial liquid absorption processes. Nitrogen oxide emissions are ultimately a function of conditions in the turbine combustor, but aqueous scrubbing of ammonia from the fuel gas reduces its nitrogen content ahead of that point. Makeup water requirements fall as much as 40% below those of conventional steam plants because most of the output is generated by the combustion turbine cycle. Solid and liquid effluents are thus lower than those from any other coal-based power technology.

lems for the resource-, cost-, and environment-conscious utility industry. It doesn't handle eastern bituminous coals well because they tend to become sticky and cake, impeding reactor operation. (Since the 1940s the caking problem has been solved by mechanical stirring, but this adds to equipment complexity and cost.) Also, the coal throughput of a fixed-bed gasifier is relatively low, because the gas velocity, and thus the oxidant flow, is limited.

### The slagging gasifier

A recent adaptation of the Lurgi solves many of the foregoing problems. British Gas Corp. (BGC) has substituted a refractory-lined hearth for the Lurgi grates, permitting higher temperature operation that yields molten slag rather than solid ash waste. Because less steam is required to control the higher temperature, the proportion of oxygen in the incoming gas volume is greater than in the fixed-bed gasifier. Reactions therefore proceed faster, coal is consumed up to three times faster, and gas production is thereby increased. By-product hydrocarbons are recovered in liquid form (by quenching the product gas stream) and recycled for further reaction, until their extinction.

The BGC-Lurgi slagger looks promising. A prototype (approximately half-scale) at Westfield, Scotland, is now about four years old and has been run at feed rates up to 350 t/d. One measure of its performance is the ratio of combustible carbon monoxide to noncombustible carbon dioxide in its gas yield. This ratio ranges from 30 to 60 for the slagger, compared with only 1 or 2 for the Lurgi. Also, the markedly lower steam consumption of the slagger reduces the need for wastewater treatment.

### The fluidized-bed gasifier

Efforts to achieve more intimate carbon-oxygen contact led to the fluidized-bed gasifier. For this process the coal is more finely ground and the oxidant velocity is higher, sufficient to suspend the coal in a turbulent fluid medium of coal and gas. Coal particles fall, are partially consumed, and rise again. Mixing is thorough, and each coal particle is constantly exposed to new oxidant and to gases throughout the depth of the fluidized bed. Typically, the temperature profile is uniform from bottom to top.

But what must this temperature be? Low enough for the ash not to become sticky, preferably below 2100°F (1150°C), as in a Lurgi, and high enough for the partial oxidation reactions to proceed, above 1600°F (850°C). The range is narrow and it slows the process throughput; up to one-hour residence time is needed for reacting some older coals (anthracites) at the low end of this temperature range.

The fluidized-bed process presents its own practical engineering problems, especially in materials handling. Because the temperature is intentionally uniform throughout the bed, it is difficult to add new coal, especially the caking types that quickly volatilize and contribute their liquid hydrocarbons to the exiting gas stream. The only evident cure is pretreatment of the coal—oxidation in a separate reactor to convert a caking coal to a noncaking. But this in turn produces its own emissions to be cleaned, adding to the system cost.

Also, the ash removed from a fluidized bed (to make room for new coal) inevitably contains some unreacted carbon, requiring the downstream addition of a combustor to oxidize it completely. This entails additional water for temperature control and produces yet another flue gas stream. In sum, the fluidized bed provides excellent carbon-oxygen contact but may require pre- and postgasification steps that would compromise its economy and reliability for utility power systems.

### The entrained gasification system

In the entrained system there is no bed. Coal and gas particles flow together in a cocurrent stream. A given bit of coal is therefore exposed only to the gas that surrounds it, but thorough reactions are

## GASIFICATION CHEMISTRY

As implied by the term *partial oxidation*, coal gasification takes advantage of some oxidation reactions and stops short of others. Simplistically, these occur in time sequence, the first being a complex of devolatilization reactions as the coal is rapidly heated, thus:

$$\text{Coal} \rightarrow CH_4 + CO + H_2 + CO_2 + H_2O + \text{heavy hydrocarbons} + \text{char}$$

Heavy hydrocarbons vary in their composition and in their reactivity to simpler gaseous form. The extent is a function of time and temperature in the process environment.

In contact with oxygen and steam, the hot char (a mixture of less-reactive carbon and ash) produces these major gasification reactions:

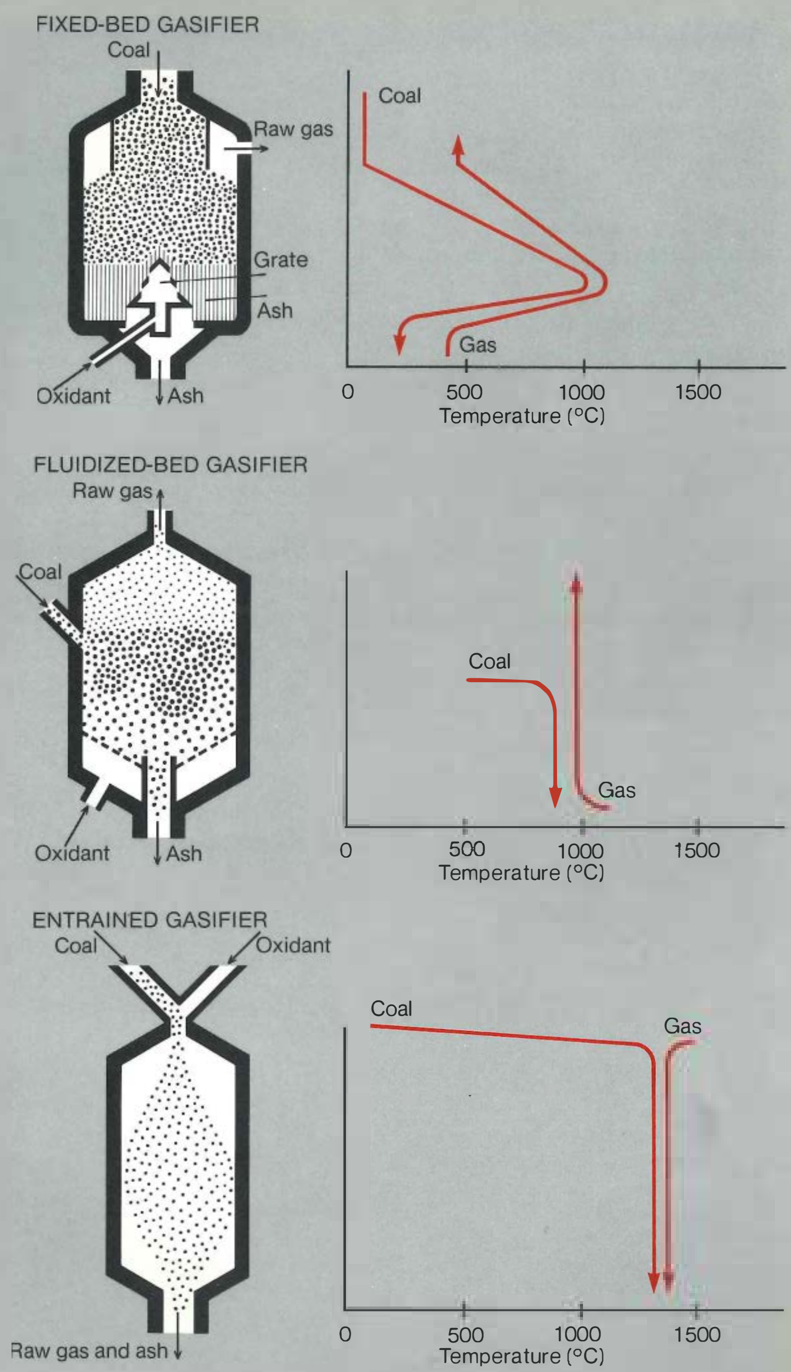
$$C + \tfrac{1}{2}O_2 \rightarrow CO$$
$$C + H_2O \rightarrow CO + H_2$$
$$C + CO_2 \rightarrow 2CO$$

Although the first of these is exothermic, the other two are endothermic, and the net effect of their simultaneous occurrence is endothermic. The resultant carbon monoxide and hydrogen are combustible products, the essential constituents of synthetic gas (also known as synthesis gas or syngas).

Complete oxidation, or combustion, would require more oxygen per pound of coal, and these further reactions would proceed:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$
$$C + O_2 \rightarrow CO_2$$
$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O$$
$$CO + \tfrac{1}{2}O_2 \rightarrow CO_2$$

The endothermic gasification reactions are driven by exothermic combustion in a small portion of the coal. Dominance of the gasification reactions is controlled by the ratio of oxidant to coal and by the time and temperature of contacting.




Differences among gasification reactors are distinguished by these flow schematics and temperature profiles for fixed-bed, fluidized-bed, and entrained gasifiers. The combustion zone is at the bottom of the fixed-bed gasifier, and gasification occurs through a range of decreasing temperatures as gases rise through the reactor. Simultaneous combustion and gasification occur at essentially constant temperature throughout the other two types.

Coal particle size is important (about 3–50 mm, < 8 mm, and < 0.1 mm, respectively, for the three gasifiers), as is the relative oxidant input for optimal reactions and energy transformation. Coal residence time in the reactor is a further control on process reactions and thereby on the mix of raw gas products, the formation of by-products, and the character of ash. Higher temperatures encourage faster reactions and gas production; thus, the entrained gasifier typically has the highest capacity.

*Adapted from an American Lurgi Corp. drawing* promoted by very high temperatures, 2400–2700°F (1300–1500°C). Several practical implications stem from this concept.

□ Because the coal particles are not in physical contact with each other, they cannot stick, and in this respect the system works well with any coal.

□ The reactor is mechanically simple; it does not require a distributor plate, grates, or stirring apparatus.

□ High temperature means molten slag residue and a need for refractory lining materials.

□ High temperature also means fast reactions—within as few as five seconds—and therefore permits high coal throughput and gas yield.

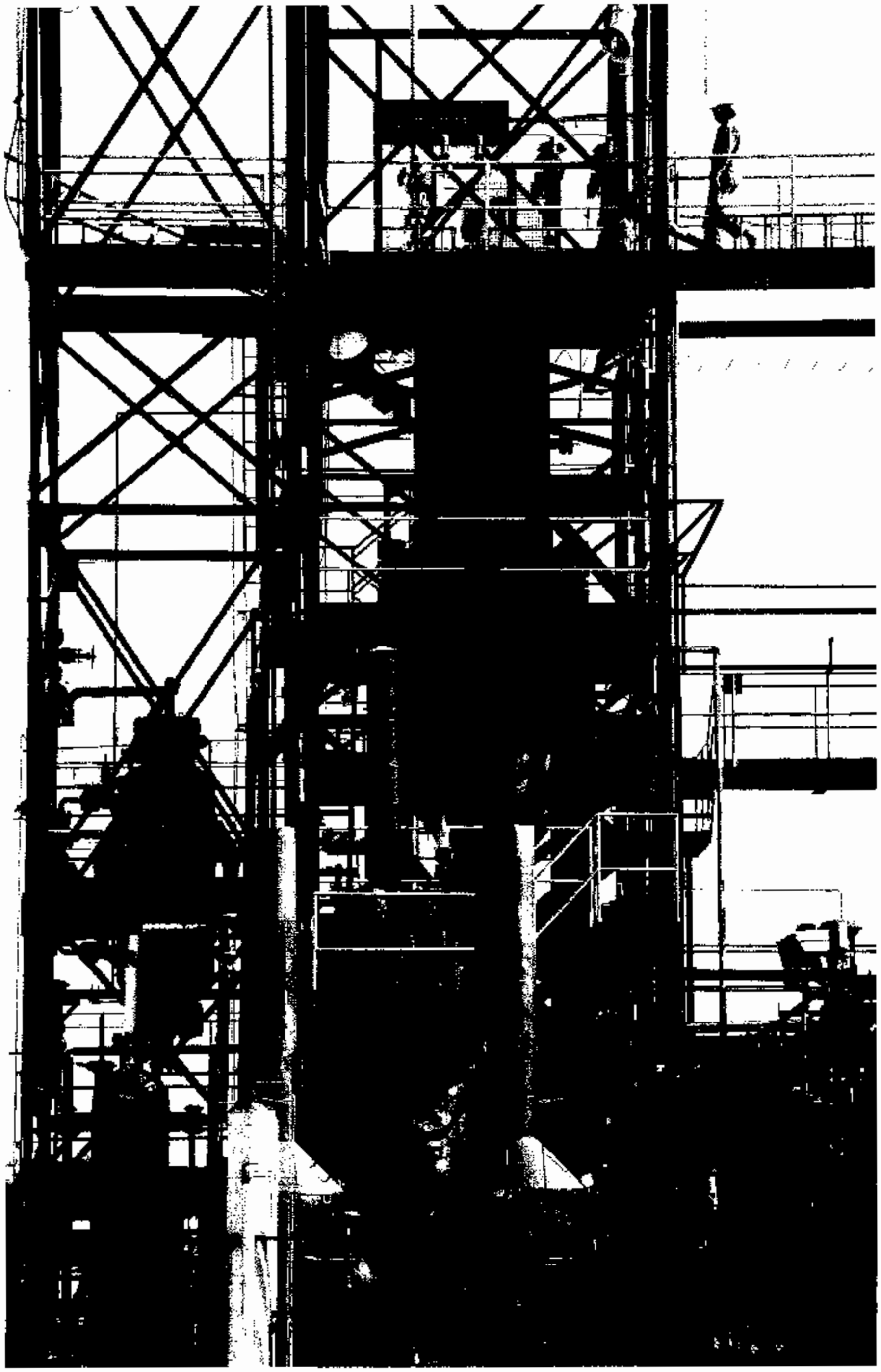
Most of these implications favor the system. Higher temperatures could even be pursued, but the resultant increased coal throughput and gas yield would be offset by the cost of exotic refractories and the cost of the coal burned solely to create the higher temperature. High coal throughput also poses further problems of material handling, and the solutions evident today favor the use of some coals more than others.

**Slurry handling**

Dry pulverized coal is difficult to meter accurately for safe process control. A coal-water slurry, on the other hand, is easy to meter, but the water must be boiled off in the gasifier. This means more combustion, calling for more oxidant and, in turn, for additional expensive oxygen plant capacity.

The amount of water in the slurry varies with the coal type. Eastern bituminous coals can generally be pumped at a high solids concentration (the ratio of coal to total slurry weight). Southwestern and North Dakota lignites, in contrast, yield pumpable slurries only at

The first coal gasifier to be integrated with a U.S. utility generating unit will probably be based on this pressurized, single-stage entrained system designed and built by Texaco, Inc., at Montebello, California. Its coal capacity is 15 t/d, a feed rate that has been scaled up to 150 t/d in Germany and will be increased to 1000 t/d for a 100-MW demonstration plant planned for the Southern California Edison Co. system.



The largest second-generation coal gasifier in the United States today is this atmospheric, two-stage entrained system designed and built by Combustion Engineering, Inc., at Windsor, Connecticut, with joint funding from DOE, EPRI, and the manufacturer. Its coal capacity is 120 t/d. Completed early in 1978, the process development unit has since been operated in a series of tests using Illinois and Pittsburgh No. 8 coals.

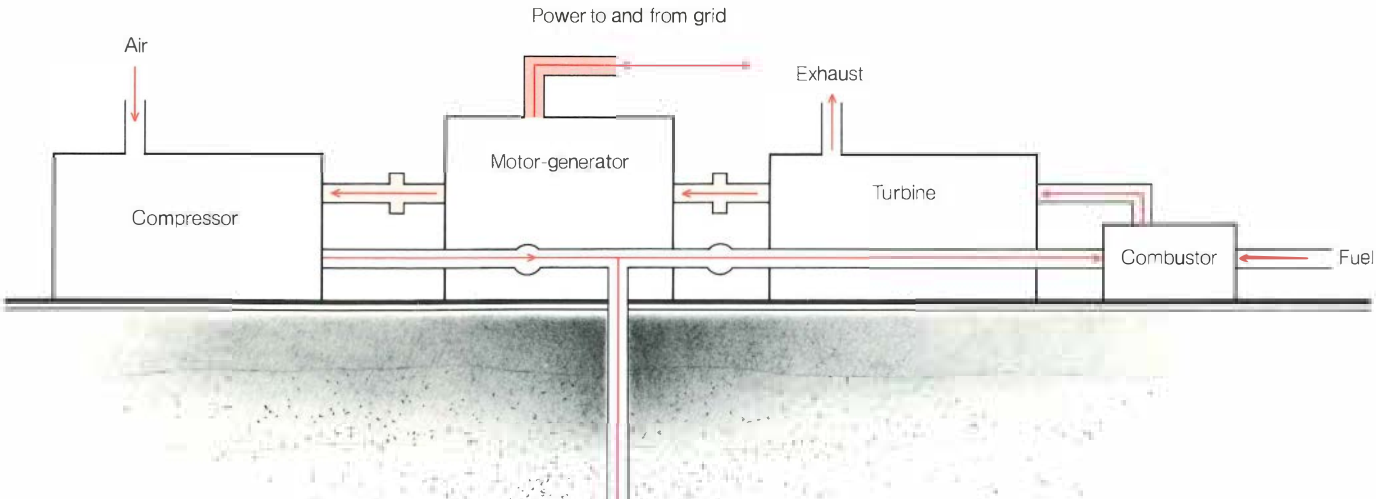
a much lower solids concentration. Some method of coal pretreatment (if one can be devised) would offset the efficiency and economic penalties of dilute slurries.

**Electric utility application**

For electric utilities, the prime prospective use for any coal gasification system is its direct integration with a combined-cycle power plant. In this application, the gas is burned under pressure to drive a gas turbine. The hot exhaust then heats water for a steam turbine. Both turbines are coupled to generators, and their combined efficiencies exceed that of either machine alone. This conserves fuel and offsets the cost of converting the coal to gas.

Integration of gasifier and power plant means more than common siting. It involves functional connections and shared use of steam, oxygen, water, electricity, and gas between gasifier and generator auxiliaries. Design of such a facility is a problem all its own and is the subject of urgent utility development under EPRI sponsorship. Historically, gasification processes have been operated under steady-state conditions, but power plants must be able to "maneuver" up and down, matching output to electricity demand. At the present stage of development, it appears that a pressurized entrained system best affords this capability for integrated operation.

But even though such maneuvering must be possible, the eventual aim of integrating coal gasification with combined cycles is to meet continuous (base-load) demand. This means long-running reliability and production of electricity at the lowest unit cost. Gas from coal can thus become a clean-burning substitute for direct-fired raw coal in the electric utility market and eventually, a substantial replacement for today's oil or natural gas.



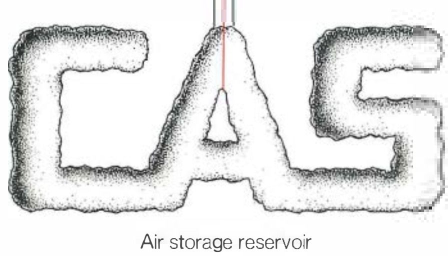

# Eighty Atmospheres in Reserve

**EPRI, DOE, and several utilities are exploring the use of compressed air in underground reservoirs as an energy storage option.**

Nuts and bolts of the compressed-air storage (CAS) option: During off-peak periods, inexpensive grid electricity from coal-fired or nuclear power plants runs a combination motor-generator in a motor mode, which in turn operates a compressor. Air is compressed, cooled, and pumped into an underground storage reservoir. The reservoir may be millions of cubic feet in volume and thousands of feet below the surface. There the air remains, at pressures up to 8 MPa (80 atm), until peaking power is required. At that point, the air is released into a combustor at a controlled rate, heated by oil or gas, and expanded through a series of turbines. The turbines drive the motor-generator in a generator mode, thereby supplying peaking power to the grid.

This system can save one-half to two-thirds of the precious oil or gas that a conventional gas turbine peaking system would require. In a standard gas turbine, a large part of the turbine's shaft power (supplied solely by oil or gas) goes into powering the compressor. In CAS, the compressor is powered by off-peak coal-fired or nuclear power, freeing all the turbine's output for electricity generation.

Existing CAS designs are not pure energy storage systems because some oil or gas, albeit a reduced amount, is needed to make up for the heat lost in the compressor coolers and to help expand the compressed air. Nevertheless, research is under way to cut back—or eliminate entirely—this oil or gas requirement.



One dark night an electric utility's surplus energy vanishes underground. The next day, on command, it surfaces as a hiss of pressurized air, spinning the turbines of a power plant just in time to meet a sharp rise in electricity demand. Sorcery? No—compressed-air energy storage.

If a utility is able to produce an excess of cheap baseload energy from coal- or nuclear-fired plants during an off-peak period, but must resort to expensive peaking power from such equipment as oil-fired gas turbines, it may make economic sense to store the extra baseload energy for use in those peak demand periods. Some utilities are already storing energy with pumped-hydro installations, and many more would like to do so. However, it is becoming difficult to find acceptable sites for conventional, aboveground, pumped-hydro storage.

Compressed-air storage (CAS) could be one acceptable alternative. A CAS plant takes surplus, inexpensive baseload electricity, generally at night and on weekends, and uses it to compress air into an underground reservoir that may be millions of cubic feet in size and thousands of feet below the surface. Rock beds, salt domes, and aquifers are all candidates for siting compressed-air storage reservoirs, according to Thomas Schneider, manager of EPRI's Energy Storage Program. Such underground siting would be less costly than building aboveground pressure vessels.

The air would remain in these reservoirs at pressures up to 8 MPa (80 atm) until electricity demand increased sufficiently to bring in peaking power. At that point, a controlled flow of air would be released from the reservoir into a combustor, heated to high temperatures by oil or gas, and then sent through a series of turbines, which would in turn drive the plant's electric generators.

Because contemporary versions of CAS use either oil or gas in the turbine train, they are not pure energy storage systems. Nevertheless, these systems are expected to save perhaps two-thirds of the costly oil or gas required by a conventional gas turbine peaking system, replacing it with relatively inexpensive baseload energy stored as compressed air.

## Close scrutiny

CAS has yet to take its place in the electric utility generation mix of this country, but it's already a reality in Huntorf, West Germany, where the first commercial CAS plant, a 290-MW unit, went into operation last December. The plant, situated over two 150-km$^3$ ($\sim 5 \times 10^6$ ft$^3$) salt caverns, was designed and built by Brown Boveri Co. for the German utility Nordwestdeutsche Kraftwerke Ag. So far, reports Z. Stanley Stys, vice president of Brown Boveri in New Jersey, the system is a success.

In the United States, CAS is being closely scrutinized by EPRI, DOE, and individual electric utilities on the lookout for near-term energy storage options. EPRI and DOE are presently cosponsoring three preliminary CAS engineering-design studies. The studies are led by three electric utilities, each of which is covering its own costs for participating in its project: Middle South Services, Inc. (MSS); Potomac Electric Power Co. (Pepco); and Public Service Indiana (PSI). Four other utilities—Commonwealth Edison Co., Illinois Power Co., Central Illinois Public Service Co., and Union Electric Co.—are also participating in the PSI project. These primarily analytic studies, worth a total of $9 million, address design, economic, environmental, safety, and siting considerations. Each focuses on one particular storage medium: MSS, salt; Pepco, rock; and PSI, aquifers. The Pepco study is also investigating underground pumped hydro.

The MSS study is expected to be completed this fall; the Pepco study, in early 1980; and the PSI effort, a year later. CAS proponents hope that these three utility-led projects, smaller privately and publicly funded studies, and the Huntorf experience will give U.S. utilities the information they need to consider CAS for near-term load-leveling.

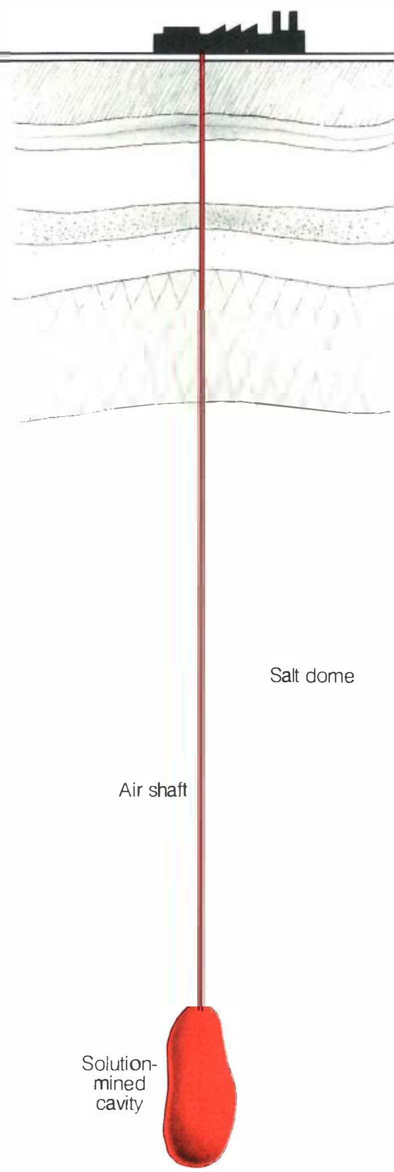
## Siting

An unusual storage option, CAS poses some unusual problems. Siting a CAS installation is difficult. There are rock beds, salt domes, or aquifers in just about every major U.S. service area, according to Schneider, but that doesn't necessarily mean they are good CAS sites. Extensive literature searches and actual field investigations are necessary to identify and confirm prime sites. In some cases, utilities may be faced with a surfeit of potentially good sites and the problem is to systematically select the best site for the first installation. For instance, there are some 47 salt domes in the area MSS is considering; the utility deduced that 10 of these domes had CAS potential. An exhaustive survey of geology, topography, and utility system considerations has since narrowed the choice to 3.

A CAS reservoir must be stable under daily temperature and pressure cycling. If kept within limits, this daily cycling may not pose any problems, but there is little experience in the daily cyclic operation of pressurized underground caverns. Accordingly, engineers are seeking the sturdiest formations available for the first plants, as well as proceeding with a few extra precautions. For instance, they propose that reservoir air temperatures be kept down to about 50°C (125°F, the approximate temperature of surrounding formations) by using intercoolers and aftercoolers in the compressor train. Similarly, pressure fluctuations within the reservoirs will be restricted to a moderate range. "As more is learned about the performance of underground reservoirs under repeated temperature and pressure cycling," comments Schneider, "some of these design restrictions may be relaxed."

The reservoir must also be tight enough to prevent significant air leakage through fissures. While a small loss of pressure would be acceptable, a large loss could prove costly in terms of system efficiency. If sufficient escaped air is routed in such a way that uncontrolled pressure builds up near the surface, a blowout is a serious possibility. The likelihood of these prob-

Solution-mined salt caverns are one possible CAS medium. A narrow well would be drilled into a salt dome and fresh water continuously pumped in to dissolve the salt. The resultant brine would be pumped out. The process would continue until the desired storage volume is reached.




lems occurring is largely unknown, Schneider emphasizes; ongoing and future research will have to provide the answers.

### Salt, rock, or aquifer?

Each of the three types of reservoir has its own peculiar advantages and disadvantages, points out William Stevens, EPRI project manager for thermal and mechanical energy storage. Salt domes, for example, are the least expensive to develop; the solution-mining technique entails drilling a narrow well into a salt dome and continuously pumping in fresh water. Over a period of time (the two Huntorf caverns took 12 and 16 months to mine), the salt dissolves. While water is being pumped in, the resultant brine is pumped to the surface for disposal in an evaporating pond or natural saltwater body. The brine might also be injected underground if saltwater aquifers are available. The solution-mining process is continued until the desired cavity size has been reached. Salt caverns (some of which were developed in this way) have been used over the years for the storage of oil and natural gas. Another advantage of salt is that the contact with water during the solution-mining process heals small fissures and thus helps prevent air leakage.

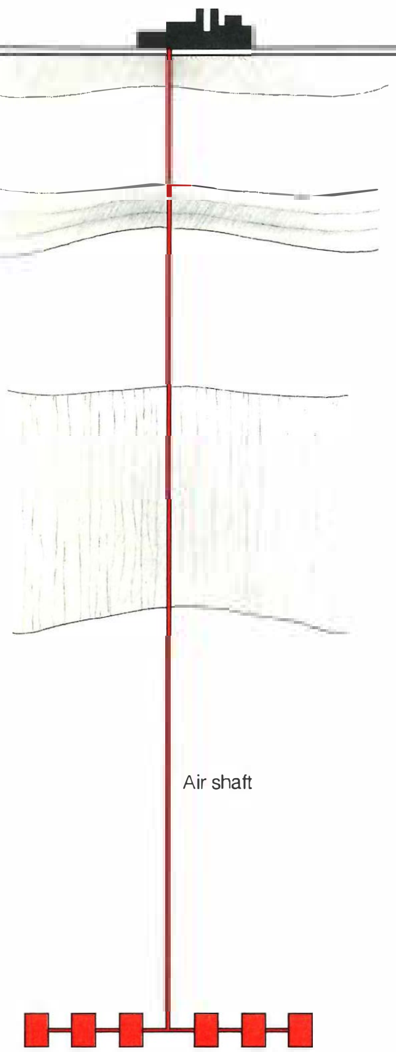
Salt also has its disadvantages. One is the tendency to flow, or creep, when under pressure over a period of time, a tendency aggravated by elevated temperatures. This phenomenon could cause a gradual reduction in cavern volume. Accordingly, the salt caverns at Huntorf were designed somewhat larger than necessary. The caverns will be periodically monitored by specially designed instruments, but they are expected to last the lifetime of the facility, some 30–50 years, with very little shrinkage. Salt creep is not entirely destructive—it too works to heal cavern fissures.

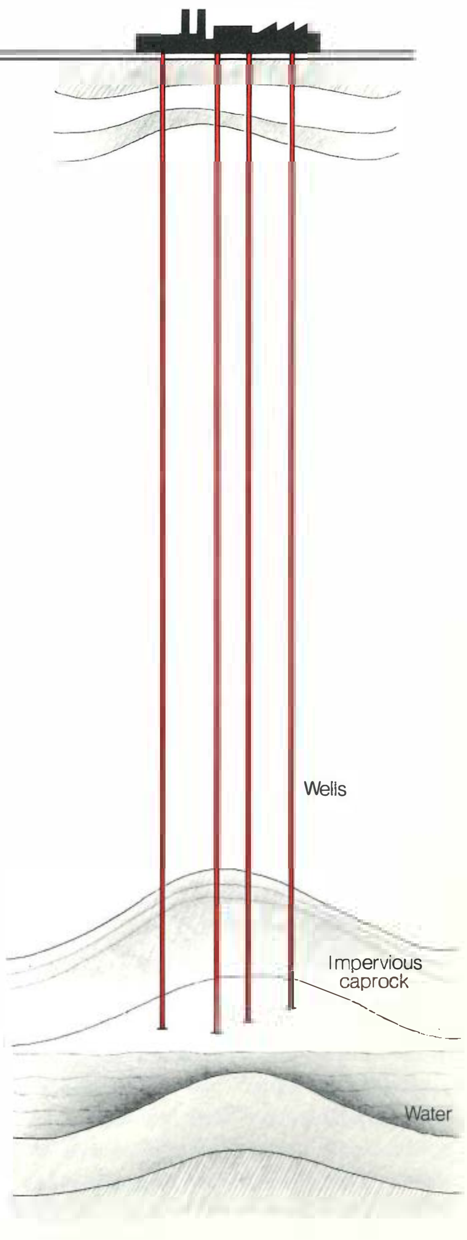
Another potential drawback of these reservoirs is salt carryover to the plant's turbines, where it could corrode the blades. Again, experience at Huntorf indicates a solution: the Huntorf system is designed so that air velocities near cavern walls are never high enough to carry brine droplets up into the turbines.

Advantages of hard rock as a compressed-air storage medium include seemingly abundant potential sites and a well-established excavation technology. On the debit side, however, is the difficulty of knowing, before excavation, that the deep rock is solid and competent enough for caverns. Rock may be fraught with faults that could begin to move under temperature and pressure cycling; bolting to shore up the weak spots is a possible solution. Fissures in the rock could also permit air to escape, which could be solved by grouting to seal the cavern. (Natural caverns are generally not considered for compressed-air storage because of the difficulty of exploring, reinforcing, and sealing them properly.)

A series of tunnellike caverns mined from hard rock is another CAS possibility. The necessary mining technology is well established, if capital-intensive. Natural caverns are unsuitable for CAS because of the difficulty of exploring, reinforcing, and sealing them properly.

Aquifers of sand, sandstone, or gravel are yet a third CAS prospect. Numerous wells would be sunk through an impervious caprock and into the porous aquifer beneath for the injection and discharge of compressed air. The pressure of the surrounding water confines the compressed air.




A hard-rock reservoir will generally be more expensive to develop than a salt cavern. Standard mining technology is labor- and equipment-intensive. Before storage tunnels can be mined, a shaft large enough to lower miners and heavy equipment must be excavated. Detailed investigations of the cost of reservoir excavation are part of the EPRI–DOE study.

Sand, gravel, or sandstone aquifers, like rock beds, are widely available in the United States. In principle, they could be developed into compressed-air reservoirs easily without excavation. A series of wells would be sunk into an aquifer's caprock and the porous medium below it; air would then be injected, forcing the water of the aquifer away from the shaft. During air discharge, water pressure would drive the air out of the well. This technology is already familiar to the natural gas industry, which uses aquifers for storage. However, aquifers used to store compressed air would be subject to daily cycling, unlike those used to store natural gas over the period of a season. High porosity and permeability are necessary to allow the rapid charging and discharging of the CAS system through a reasonable number of wells. The aquifer must also have an impermeable caprock overhead to prevent air from surfacing, as well as a caprock topography that prevents air from escaping laterally. Clearly, the basic experience gained by the natural gas industry must be expanded for aquifers to be feasible for CAS storage.

### Equipment questions

In a standard gas turbine power plant, the turbine simultaneously powers both compressor and generator—the compressor injects combustion air directly to the combustor and to the turbine. The entire assembly operates at one time. About one-half of the oil or gas used by the turbine plant goes into power for the compressor; only one-quarter of the fuel energy actually appears as electric power output; the rest is lost as exhaust heat.

CAS calls for some changes in this basic configuration: a synchronous motor-generator (M–G), connected by clutches to either the compressor or the turbine, replaces the generator. During charging, grid electricity powers the M–G as a motor, which in turn drives the compressor. During discharging, the compressed air powers the turbine, which in turn runs the M–G. The M–G now operates as a generator that supplies power to the grid. Because the fuel energy ordinarily required to power the compressor is replaced by stored compressed air, two-thirds of the oil or gas used in a standard turbine is saved, being replaced by grid electricity generated with coal or nuclear energy.

Component technologies for CAS are available; compressors, turbines, clutches, generators, and motors are off-the-shelf items. Yet some modifications will be necessary. For instance, standard steam turbines operate at high pressures suitable for CAS applications but lack appropriate metallurgy; standard gas turbines have the right metallurgy, but operate at relatively low—and therefore unsuitable—pressures. Westinghouse Electric Corp., PSI's subcontractor, will redesign standard turbines to suit CAS system requirements, according to Antonio Ferreira, EPRI project manager for energy storage and hydraulic engineering. Westinghouse will also investigate equipment reliability, availability, and cost.

The other two utilities, MSS and Pepco, which are studying modified high-pressure steam turbines from Brown Boveri, will also make equipment reliability, availability, and cost investigations.

### Fuel problems

Ultimately the use of oil or gas in the CAS system's turbine train is likely to become a liability. Should the United States premium fuel supply of high-quality fossil fuels be interrupted, or if federal policies throttle it further, any system that uses even relatively small amounts of that fuel is at a disadvantage, and a utility might be reluctant to install such a system.

Engineers are aware of this and are probing a number of possible ways to cut back or eliminate CAS's use of oil or gas. One is the use of recuperators, which use the waste heat from the gas turbine exhaust to preheat the air coming from storage. This would result in less fuel required for the same power output. But recuperators also present equipment problems—they are not yet made for the pressure, temperature, and operating conditions CAS imposes. The EPRI–DOE studies will research whether CAS recuperators can be manufactured economically with the necessary reliability.

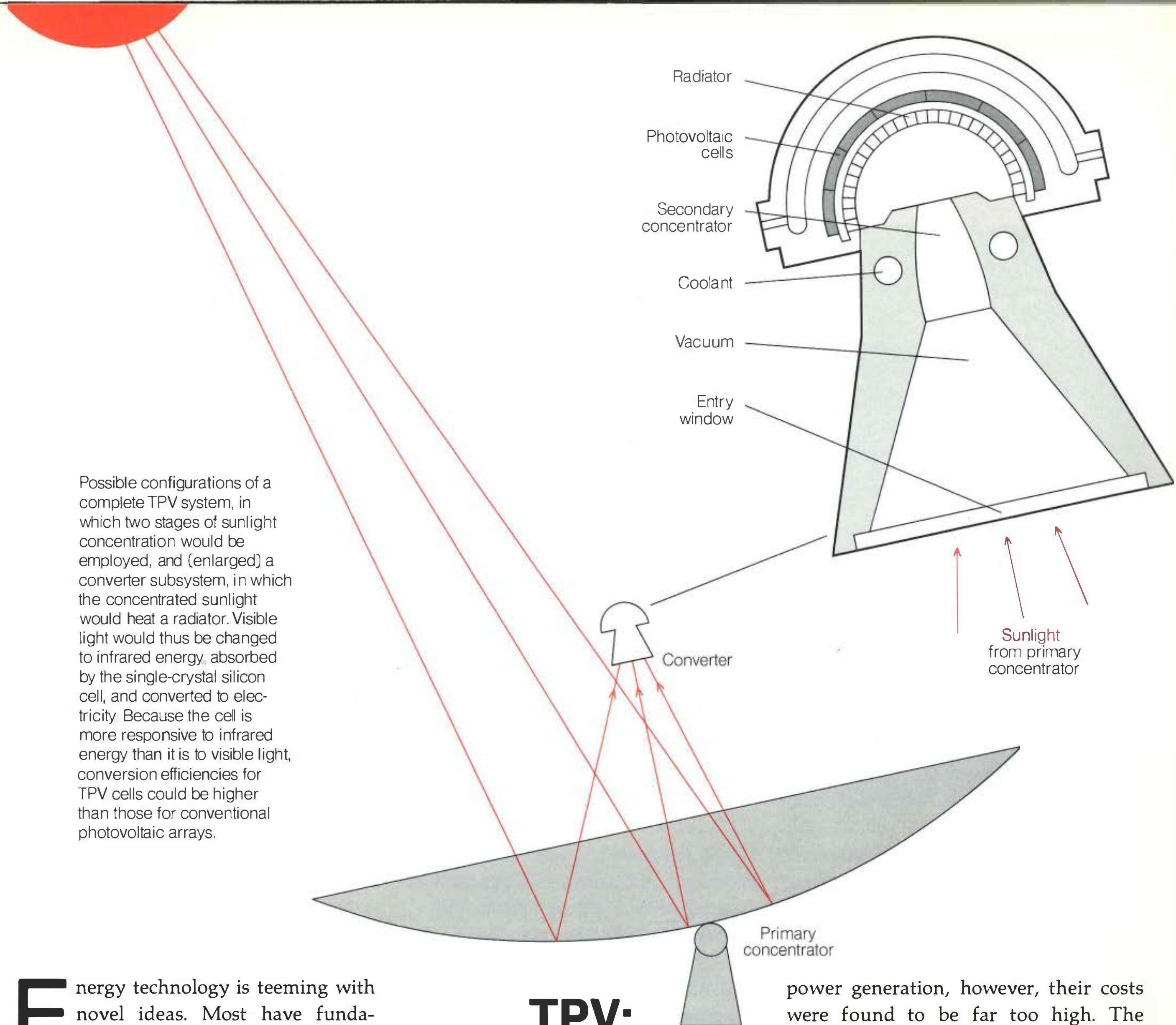
Another way to conserve oil and gas would be to store the heat resulting from compression and recover it later to warm turbine-bound air. This considerable heat would otherwise be rejected by intercoolers to the outside environment. A recently completed joint effort between EPRI and England's Central Electricity Generating Board (CEGB) explored two versions of this scheme: a hybrid design that uses stored heat of compression and a reduced amount of fuel, and an adiabatic alternative that relies entirely on the heat of compression and uses no fuel at all. The design proposed by CEGB for the hybrid system would store the heat in an aboveground pressure vessel made of steel, concrete, or cast iron, and filled with fireclay or cast-iron pebbles. Because it involves substantially higher temperatures, the adiabatic system, however, requires an advance in the state of the art of both thermal energy storage and compressor designs before it can be realized.

One more way of circumventing the oil-gas problem is to use another fuel. In a recent EPRI project, United Technologies Research Center (UTRC) studied the possibility of using a coal gasification process in conjunction with compressed-air storage. However, UTRC reports that gasification may be better suited to continuous operation than to CAS's cyclic schedule. Perhaps a better solution, suggests Stevens, is the use of synthetic oil derived from coal liquefaction, which could be easily stored and used as needed. Still another possibility is the use of coal in fluid-bed combustors, a concept that is now being assessed by EPRI and DOE.

### If they could, would they?

With siting, safety, design, and environmental questions now being answered, utilities looking for less expensive peaking power will be better able to consider a CAS installation. If a suitable site is available, if the reservoir can be developed at a reasonable price, and if an oil or gas supply (or an alternative) is assured, the utility next must evaluate how well CAS fits into its system. One prerequisite is inexpensive baseload power. The utility must also consider whether other peaking alternatives would better suit its needs. "Very few utilities have gone through this analysis," comments Lewis A. Wilson, manager of advanced energy programs at MSS. "It's complicated, and the necessary computer codes haven't been available until recently." Codes that factor CAS into a utility system are being used in the three EPRI–DOE studies. Final results are not yet in, but the cost of energy generated by CAS is expected to be competitive with that generated by underground pumped hydro and certainly less expensive than that produced by a standard gas turbine.

Even if all studies prove positive, concludes Schneider, one final nudge will be necessary to set this new technology in motion: the initiative to do it. ■




Possible configurations of a complete TPV system, in which two stages of sunlight concentration would be employed, and (enlarged) a converter subsystem, in which the concentrated sunlight would heat a radiator. Visible light would thus be changed to infrared energy absorbed by the single-crystal silicon cell, and converted to electricity. Because the cell is more responsive to infrared energy than it is to visible light, conversion efficiencies for TPV cells could be higher than those for conventional photovoltaic arrays.

# TPV: Management Approach to High-Risk Research

**Thermophotovoltaic conversion is a new idea for electricity generation. But as an unproved concept, its development is subject to constant scrutiny by teams of experts brought together by EPRI.**

Energy technology is teeming with novel ideas. Most have fundamental drawbacks when explored in an economic context. Yet occasionally a new concept will surface whose promise is sustained under prolonged examination and whose development can be speeded in a carefully balanced atmosphere of scrutiny and support. The team approach being used by EPRI to foster thermophotovoltaic (TPV) research is a case in point.

Photovoltaic devices convert sunlight directly to electricity. Until a few years ago there were two main contenders in the research field: single-crystal silicon cells and thin films. The first were developed to provide internal power for spacecraft. When examined for large-scale power generation, however, their costs were found to be far too high. The process of growing high-quality silicon crystals does not lend itself readily to low-cost mass production, and at best, the economic barrier will be difficult to overcome. The second approach, where thin layers of semiconductor materials are deposited on an inexpensive substrate, looks more promising from a commercial standpoint, but the efficiencies of the devices tend to be low. Given the economic and performance difficulties inherent in these two technologies, EPRI's Solar Program staff was receptive to new options, "more horses in the race," as Project Manager Edgar DeMeo puts it.

When an unsolicited proposal for a

In his laboratory at Stanford University, Richard Swanson calibrates the intensity of infrared energy emitted by the radiator inside a thermophotovoltaic test chamber. The glow is shown radiating through a quartz lid, but when a cell is under test, the chamber is closed with a cell-support assembly in which a 6-mm-diam silicon cell is mounted. This cell absorbs the infrared radiation and converts it to electricity. (At this early stage of the research, the radiator is heated by electricity, not by sunlight.)

TPV cell was received from Stanford University in mid-1975, the staff saw the possibility of adding a new contender. The concept of a TPV system had the potential for high efficiency combined with acceptable area-related costs.

The high-risk, high-payoff project was initially funded at a conservative level of $85,000 for 1976. Since then, project results have warranted greater expenditure. This has come about through a series of checks and balances involving various participants, some of whom contributed to the research work itself, and others who evaluated that research. As the number of contractors and technical disciplines on the project grows, balance is achieved by increasing the number of evaluators. What evolves is a technical forum for ideas, providing an opportunity for contributors and critics alike to put forward their views on the concept and its development.

As with other solar projects, progress review meetings are held quarterly, attended by contractors, consultants, and representatives from related government programs, such as the Solar Energy Research Institute. Utilities have also been involved since the start to help keep project activity aimed at the ultimate goal of utility service.

### Conversion process

It is the realistic and goal-oriented qualities of Stanford's TPV research that has been particularly attractive to the Solar Program staff. The inventor, Richard M. Swanson, assistant professor of electrical engineering at Stanford, has been able to correlate his experimental work with a theoretical model that explains the progress achieved and points toward future improvements.

Although it is too early to tell, TPV conversion may evolve into an attractive solar-electric option for large-scale utility use. Compared with other photovoltaic approaches, its advantages include higher potential conversion efficiency and higher power density per unit area of cell. The latter allows a much reduced cell area. The major cost element, therefore, lies in the sunlight-concentrating part of the system. Whereas the cell area in a flat-plate photovoltaic array is nearly equal to the array aperture area, a TPV system can catch an equivalent amount of sunlight and via an optical concentrator, focus it onto a cell whose area is much less than the aperture area. This could greatly reduce cell costs.

It was 1974 when Swanson first thought of converting sunlight to infrared energy before converting it to electricity in a solar cell, although he later found a similar approach had been suggested previously. To achieve the change in wavelengths, he proposed placing a radiator—a tungsten heating element—between the solar concentrator and the single-crystal silicon cell. In theory, sunlight falls on a parabolic concentrator, descends to a second-stage concentrator, heats the radiator to incandescence, and passes, primarily as infrared energy, to a silicon cell. There it gives rise to electric charge motion, creating an electric current in an external load connected to the cell. The wavelength change, or spectral shift, is sought because the cell is much more responsive to infrared energy than it is to visible light.

By 1976 Swanson had achieved 7% efficiency in converting incandescent radiation to electricity. By last year this level had risen to 26%, and by 1980 Swanson hopes to achieve 35%, which may allow serious consideration of the concept for large-scale use. But there are still major engineering problems to study and solve before commercialization is possible.

One way to increase the efficiency of the cell is to cut down waste by recycling the infrared radiation that is not converted to electricity. Swanson's design incorporates a reflective coating (on the underside of the silicon wafer), which bounces unconverted heat back to the radiator to be used again. This recycled energy helps to maintain the radiator temperature at the operating level (*EPRI Journal,* March 1978, p. 25).

A second contributing factor to improved efficiency is the reduction of electrical resistance losses in the conductors, which lead the high current out of the cell. This demands precise fabrication methods to create an intimate contact between the metal layer and the silicon surface.

Another essential is clean processing of crystal wafers. Swanson's laboratory is conveniently housed in the same building as the Stanford Integrated Circuit Laboratory. Here ultraclean conditions make it possible to reach a high degree of perfection in the initial decontamination of the wafers and the subsequent controlled introduction of impurities, both of which are essential for superior electric performance of the devices.

**Branching out**

Until a year ago, the project had consisted mainly of providing seed money and a supportive environment for an original and promising idea. Milestones had been consistently met, and EPRI's 1978–1979 funding had been raised to a level of $400,000 to cover new facilities for improved cell-processing control, as well as for additional personnel. But a variety of questions remained on the optical and thermal properties of the total TPV system, so authorization to broaden the scope of the research was requested.

By early 1978, it was time to examine the project from different viewpoints and to explore some of the outstanding questions. For example, assuming positive results in the cell research, how might concentrator performance be upgraded? Is it possible to find a radiator material that does not evaporate at 2000°C and deposit on the cell surface? Interdisciplinary teams are being drawn together to help answer these and other questions, with the aim of assembling an information base and a test program capable of assessing and verifying the TPV concept as a whole and the practicability of each component.

Besides the key issue of TPV cell performance, four crucial areas remain to be studied: optical performance, thermal performance, radiator materials, and total system design. A study of the first two has recently been initiated, and contracts for the last two will be let if this study and the Stanford work continue to show positive results. "Any one component of the system could stop the project if its efficiency cannot be increased," says John Cummings, Solar Program manager. On the other hand, if one subsystem is limited by high losses, then perhaps another subsystem's performance could be substantially upgraded to compensate, thus boosting overall efficiency of the total system.

Such questions are continually debated in the interactive meetings of the contractors and project review panels and, on a broader level, in those of the utility industry advisory committees. The meetings can often bring unexpected benefits. On one occasion, after Swanson had presented his most recent results, a consultant from the integrated circuit industry asked Swanson if he was aware of a certain refinement in device fabrication. It so happened that Swanson was already in the process of incorporating the refinement. The exchange tended to solidify the approach and increased the staff's confidence in the contractor's capabilities.

A consultant's questions can also suggest new approaches to a problem. When questions on the optical requirements for TPV were brought up at a review meeting, it became apparent that this area had not been sufficiently developed. This contributed to a decision to involve other organizations in the assessment of optical and thermal issues related to the TPV concept.

As a consequence, Science Applications, Inc., was brought in, by competitive solicitation, to conduct research into performance and losses in the first-stage concentrator and in the converter subsystem (i.e., the combination of second-stage concentrator, radiator, and cell). This $200,000 project includes exploring the behavior and economics of several configurations of optical concentrators. Materials for the parabolic mirror or lens and requirements for sun tracking are also being investigated. The optical subsystem design work has been subcontracted to Itek Corp.

Thermal research tackles problems of heat losses in the three components of the converter subsystem. If results are successful, more detailed consideration will be given to candidate radiator materials, and studies of total system design will form the second phase of the project. If the radiator work goes ahead, EPRI's Materials Support Program (which is already involved in this aspect) will assume a greater role in specialized technical consultation and review.

**Utility role**

As in all EPRI solar energy projects, utility industry representatives play an important part by serving on project review panels, thereby providing industry perspective and experience throughout the research and development process. For instance, Los Angeles Department of Water and Power sends a representative who has a background in photovoltaics and is involved in other photovoltaics research at his utility. He acts as a two-way communication tie between the TPV research and development and the utility industry, both through his own utility organization and through his role as formal project liaison with the industry advisory committee associated with EPRI's Solar Program. Another example is an engineer from Pacific Gas and Electric Co., who is involved in assessing new energy sources for his company and who has been following developments in EPRI's New Energy Resources Department, which includes TPV.

As the project grows, more utility people will be brought in. This drawing of ideas into a single location can produce valuable cross-fertilization, where the participants contribute and benefit at the same time. Eventually, it will be necessary to introduce power plant experts to discuss how the total TPV system would be integrated into a utility network.

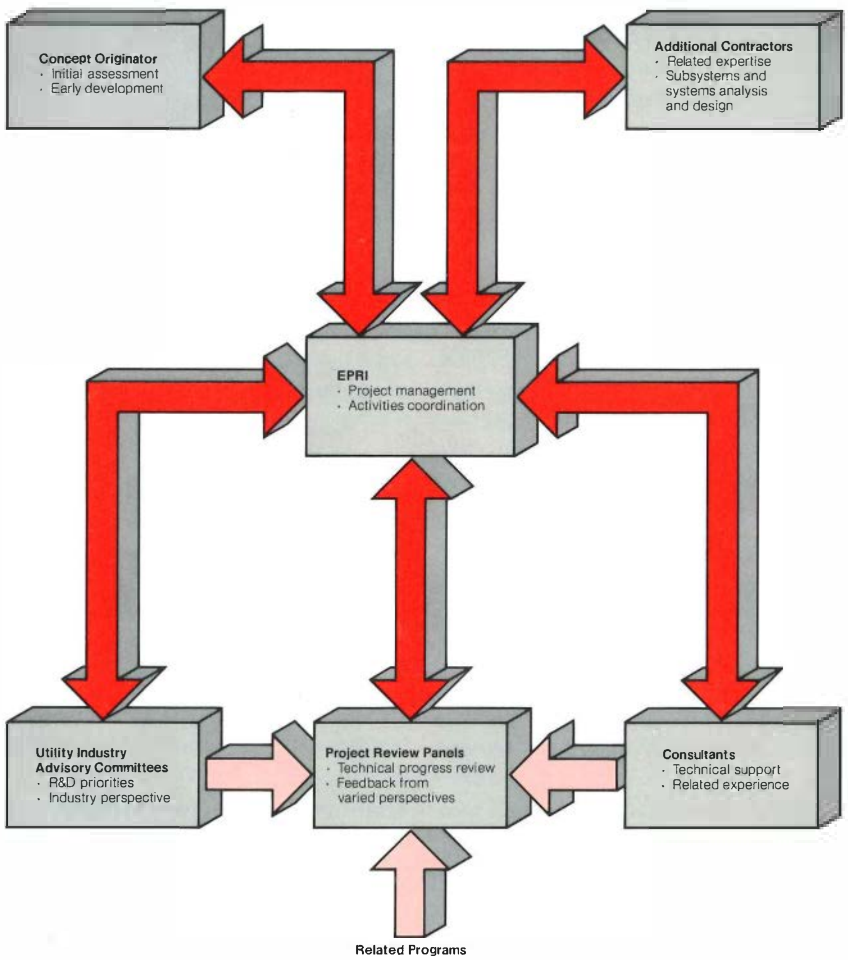
**Extending the concept**

The TPV concept is not necessarily limited to solar applications. Says DeMeo, "The source of high-temperature heat may not have to be sunlight. The concept may be useful with conventional heat sources." Consequently, an additional project to assess the feasibility of combining TPV conversion with fossil-fired heat sources was recently initiated. This study requires different skills and expertise than the solar-related TPV projects and is being carried out by Black & Veatch Consulting Engineers in a nine-month, $70,000 effort. Instead of concentrated sunlight, a combustion chamber with a mantle would supply incandescence to the solar cells surrounding it. The appeal of this unusual fossil-fueled setup lies in the potential for fewer moving parts and consequent savings in operation and maintenance. In addition, the system could show an advantage over the steam turbine in savings on initial capital outlay, particularly in small-size units. TPV power plant costs would tend to vary linearly with unit size, unlike those of the steam turbine plant.

The way in which TPV is evolving illustrates EPRI's catalytic role in teaming people who might not otherwise get together in order to speed the process of solving a real problem. There is recognition of the value in supporting a speculative idea, particularly when it is tied into a firm network of goals and evaluations. A blending of innovations, existing technology, and counsel from a wide variety of sources can reduce the chance that a needed scientific talent lies buried. And even if the idea itself has to be shelved for any reason, the experience gained from a coordinated effort like this one provides an improved basis for planning and executing future assessment and development projects. ■

**ASSESSING AND DEVELOPING A CONCEPT**

The idea is first proposed to EPRI by the concept originator. EPRI then supports an initial feasibility assessment with specific milestones. If these are achieved, additional contractors are brought in to attack other key issues identified in the early phases. Throughout the process, projects are reviewed quarterly to assess progress and provide feedback from various perspectives. Review panels include members from the utility industry, some of whom also serve on the advisory committees that make recommendations to EPRI at several management levels. Consultants are also brought in when required. In many cases, representatives from government and other related programs serve on review panels.



# Solid Waste Update

**EPA has proposed a special category for certain wastes that are found hazardous by EPA criteria.**

Electric utilities concerned about whether disposal bills for ash and sludge will soon rise dramatically from the present rate of $2 a ton have to wait a little longer for the answer.

The reason: In proposing regulations to implement the Resource Conservation and Recovery Act (RCRA) of 1976, EPA created a new class of waste called special waste. It includes any fly ash, bottom ash, and scrubber sludge that is classified as hazardous to human health or to the environment according to a series of chemical and biological tests proposed by EPA. An EPRI report published last fall (FP-878) indicated that certain worst-case power plant wastes, including ash and sludge, might be identified as hazardous under these criteria. For these special wastes, EPA has proposed postponement of the stringent rules relating to the treatment, storage, and disposal of hazardous solid wastes—rules that could inflate disposal costs to as much as $90 a ton (*EPRI Journal*, October 1978, p. 36). While treatment, storage, and disposal standards for these special wastes are being developed, general facility standards for special waste, including security measures and full monitoring requirements, have been proposed by EPA. These facility standards may be amplified at a later date.

In suggesting the new classification in the December 18, 1978, *Federal Register*, EPA conceded it had "very little information on the composition, characteristics, and the degree of hazard posed by these wastes." The limited information EPA did have indicated that "such waste occurs in very large volumes, [and] the potential hazards posed by the waste are relatively low." EPA plans to gather and evaluate the necessary information to develop standards for these special wastes and has appealed to the public for assistance in gathering this information.

## Schedules

General facility standards for special waste should be promulgated by the end of 1979, and would go into effect six months later, according to Dean Golden, EPRI project manager for solids by-product and hazardous-waste disposal. EPA plans to propose final special-waste treatment, storage, and disposal standards by June 1982, and promulgate them by June 1983.

"The fact that the special-waste category was proposed is recognition by EPA that there are high-volume, low-hazard utility industry wastes on which more data is needed to determine whether they should be treated as hazardous, nonhazardous, or somewhere in between," comments Golden. While the special-waste standards could turn out to be as stringent as the proposed hazardous-waste standards, he expects they will be "somewhere in between." He cautions that "the validity of this new category will undoubtedly be questioned by environmental organizations on one hand and by industries seeking special-waste classification on the other."

## General facility standards

While treatment, storage, and disposal standards for special waste are being developed, EPA proposed that special-waste generators be required to comply with certain general facility standards, including general site selection criteria for new facilities, security measures to limit access to the site, record-keeping and reporting measures, visual inspections, closure and postclosure requirements, and groundwater and leachate monitoring.

While including high-volume power plant wastes in the special-waste category, EPA made no allowances for low-volume power plant wastes, such as metal-cleaning, condenser cooling system, and boiler blowdown wastes. If these wastes are judged hazardous by EPA criteria, they would be subject to hazardous-waste regulation.

## New dimension

Although the special-waste category may add a new dimension to RCRA's impact on the utility industry, EPRI continues its on-going program in the identification, characterization, and disposal of utility hazardous solid wastes. Since the industry's waste output might total 200 million tons a year by 1985, Golden concludes that "the results of this program will make a valuable contribution to the data base needed by utilities and policy makers for energy and environmental solid-waste decisions." ■

# At the Institute

## Superconducting Generator Contract Awarded

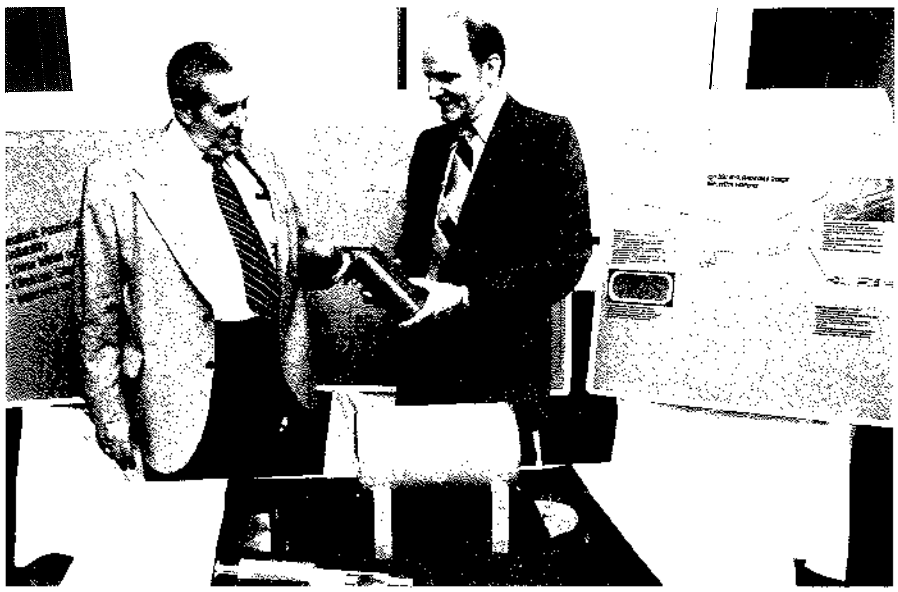
EPRI and Westinghouse Electric Corp. recently launched a jointly funded $19 million, five-year effort to design and build the world's first commercial superconducting generator. This new type of electric power generator is expected to increase the efficiency, reliability, and stability of electric power systems.

"This contract marks a major step forward in our efforts to develop superconducting technology for electric power generation," stated John Dougherty, director of EPRI's Electrical Systems Division. To date, the largest operating generator of this type is a 5-MVA machine built and laboratory-tested by Westinghouse. Other organizations are constructing generators in the 10- and 20-MVA sizes.

The 300-MVA superconducting generator to be built under this contract could supply enough electricity for about 90,000 homes and is intended for actual utility operation. "After an initial period of factory testing, the prototype will replace a conventional generator already operating on an electric utility system," explained Dougherty. That is expected to occur sometime in 1984. EPRI will select a host utility from among a group of interested utilities that have turbines compatible with the proposed superconducting generator.

Superconductivity is a property of certain metals and metal alloys that exhibit a nearly loss-free flow of electric current at very low temperatures. When this technology is applied to electric power generators, Dougherty noted, the result is a potential reduction of 50% or more in electric losses normally incurred during the generation process.

John Dougherty, director, EPRI Electrical Systems Division, (left) and Gene Cattabiani, vice president, Power Generation, Westinghouse Electric Corp., examine a model of the armature winding that will be used in the first commercial superconducting generator. The joint EPRI–Westinghouse effort concerns the design and construction of this new, more efficient generator.



Other potential advantages of the superconducting generator are lower capital costs and increased reliability. As the machine will be more compact than conventional generators, it will require less material for its construction. Manufacturers will be able to fully assemble the generator in a controlled fabrication environment, eliminating difficulties that have arisen in the past with some generators that required additional fabrication on-site. This is seen as another factor for increasing system reliability.

Also viewed as potential advantages are enhanced stability brought to the electric power system and greater adaptability to the high-voltage transmission lines that may be more prevalent in the future.

A superconducting generator is much like a conventional generator in that it produces electricity by the interaction of the magnetic fields surrounding two sets of coils called windings: the rotating field winding that is driven by the turbine and the stationary armature winding that is connected to the utility system. The difference between superconducting and conventional generators is in the field winding.

In a conventional generator, the field winding is copper and is cooled by air, hydrogen, or water. It operates at temperatures of about 82°C (180°F), and at these temperatures it experiences resistance to the flow of current, which causes electric losses.

In a superconducting generator, the rotating field winding is an alloy that becomes superconducting when cooled with liquid helium to temperatures of 4 K (−452°F). At these extremely low temperatures, there is virtually no resistance to the flow of current, and consequently, there are no electric field winding losses.

The superconducting quality is also responsible for the strengthened rotating magnetic field of the generator, ultimately increasing the stability of the entire electric system and thus reducing the probability of power outages.

## Solar for Utilities Evaluated

The value of using wind or solar cell power plants for producing electricity will vary widely from utility to utility, according to two recent studies sponsored by EPRI (ER-978 and ER-685-SY).

The studies showed that centrally located power stations fueled by the wind or by solar cells make the most economic sense when the utility's peak electricity demand corresponds to periods when the sun is brightest or the wind is strongest. The research also revealed that utilities that use substantial amounts of oil-fired generation may benefit most from the use of solar sources.

The characteristics of the utility may be as important as the availability of the wind or sun in determining if these energy sources are competitive with conventional energy sources. For example, even though the state of Kansas generally has stronger winds than upstate New York, the research indicated that wind power plants may be better for upstate New York because utilities there burn expensive fuel oil while Kansas utilities rely heavily on cheaper coal. And contrary to what many energy specialists have believed, the research showed that it is uneconomical to couple an electric energy storage facility specifically with wind or solar cell power stations. Rather, energy storage is most valuable when designed and operated for the benefit of the entire utility system.

The research, conducted for EPRI by General Electric Co., was geared to developing a procedure that individual utilities can use to determine the potential impact of these solar sources on conventional electrical systems. Such impact could conceivably affect utility decisions on buying fuel or planning additional power stations.

Although neither wind power nor solar cells are expected to have any significant impact before the year 2000, Edgar A. DeMeo, EPRI project manager for this research, said utilities need to know much sooner than 2000 how these solar systems can best be integrated into national patterns of energy supply and demand. Utilities normally plan their power needs 10–20 years in advance to allow for the long lead time required for the construction and licensing of power facilities.

Research will continue over the next two years in two new studies that will focus on the impacts of wind and solar cell power plants dispersed throughout a utility system. (The earlier research evaluated these solar sources for large-scale, central locations.) JBF Scientific Corporation, Wilmington, Massachusetts, will assess the potential impact of distributed generation systems using solar cells, and General Electric will assess wind power.

Northeast Utilities Service Corp. and the Los Angeles Department of Water and Power will assist JBF in the solar cell study. Green Mountain Power Corporation, Southwestern Public Service Company, and Pacific Gas and Electric Company will assist General Electric in the wind study.

## $NO_x$ Control Technique Investigated

EPRI has contracted with Kawasaki Heavy Industries, Japan, to evaluate a new process for controlling $NO_x$ emissions from coal-fired power plants. This jointly funded, $1.5 million project will design, construct, and operate a 2.5-MW pilot plant for $NO_x$ removal.

Developed by Kawasaki and the Electric Power Development Co., Japan, the process is based on the concept of selective catalytic reduction (SCR). SCR is a postcombustion technique that catalytically converts the oxides of nitrogen in the stack gas to nitrogen and water, using ammonia as a reducing agent.

"Although the SCR process has been shown to be up to 90% effective in controlling $NO_x$ in small-scale laboratory and pilot tests in Japan, further research on U.S. coals is needed to accurately define the cost, complexity, reliability, and the impact on the operations of power plant equipment," reports EPRI Program Manager Donald Teixeira.

The pilot plant will be installed at the EPRI Emissions Control and Test Facility at the coal-fired Arapahoe Station of Public Service Co. of Colorado. EPRI tests, which are scheduled from November 1979 to June 1980, will provide information on the performance, cost, and operational and environmental implications of SCR technology.

Utility interest in $NO_x$ control in recent years has been prompted by the stringent standards being considered by EPA for the early 1980s. EPRI's major effort focuses on developing low-cost methods of combustion modification to prevent $NO_x$ formation. Although it is hoped these methods will provide sufficient control of power plant contributions to $NO_x$ emissions, the degree of reduction that will be achieved by combustion modification is unknown at this time. Therefore, research on postcombustion, such as the SCR technology, is being initiated.

## S. David Freeman Elected to EPRI Board

S. David Freeman, chairman of the Board of Directors of the Tennessee Valley Authority (TVA) in Chattanooga, Tennessee, was elected to the EPRI Board of Directors on February 1, 1979, following the resignation of Aubrey J. Wagner, retired TVA board chairman. Freeman will serve until May, when he will stand for election to a four-year term.

Freeman was designated TVA board chairman in May 1978 for a term expiring in May 1984. Before his appointment, he was a member of the White House energy staff, serving as assistant to President Carter's energy adviser, James Schlesinger. From October 1974 to November 1976, Freeman was a special energy and resources consultant to the Senate Commerce Committee.

He served as director of the Ford Foundation's Energy Policy Project from September 1971 to October 1974, and is the author of *Energy: The New Era.* In addition, Freeman led an energy policy staff in the President's Office of Science and Technology from December 1967 to December 1971, and from 1961 to 1965 he served as assistant to the chairman of the Federal Power Commission.

A native of Chattanooga, Freeman, 53, received a civil engineering degree from the Georgia Institute of Technology in 1948 and a law degree from the University of Tennessee in December 1956. He started with TVA as an engineer in 1948 and in 1956 became a TVA attorney.

Freeman is a member of the Order of the Coif (an honorary legal fraternity), the American Bar Association, the Bar of the District of Columbia, and the Bar of the U.S. Supreme Court. He is a licensed professional engineer in Tennessee.

# Calendar

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

**MAY**

**14–16**
**Advanced Electrical Transmission Lines Workshop**
Aspen, Colorado
Contact: Mario Rabinowitz (415) 855-2280

**31–June 1**
**Over/Under Capacity Planning Workshop**
Denver, Colorado
Contact: Eugene Oatman (415) 855-2629

**JUNE**

**25–27**
**Second EPRI Symposium on Electric Utility Load Forecasting**
Denver, Colorado
Contact: Barbara Williams (415) 855-2624

**25–28**
**National Fuel Cell Seminar**
Bethesda, Maryland
Contact: Arnold Fickett (415) 855-2554

**JULY**

**8–13**
**Fifth International Conference on Wind Engineering**
Colorado State University, Colorado
Contact: Phillip Landers (415) 855-2307

**AUGUST**

**12–17**
**International Conference on the Fouling of Heat Transfer Equipment**
Indian Lake, New York
Contact: Isidro Diaz-Tous (415) 855-2826

**SEPTEMBER**

**19–21**
**International Symposium on Controlled Reactive Compensation**
Varennes, Quebec
Contact: Narain Hingorani (415) 855-2309

**OCTOBER**

**16–18**
**Second National Symposium on Environmental Concerns in Rights-of-Way Management**
University of Michigan
Contact: Robert Kawaratani (415) 855-2589

## Foreign Uranium Supply

The encouraging prospects for imported uranium and the potential advantages to U.S. utilities are discussed in a report recently released by EPRI.

*Foreign Uranium Supply* (EA-725), prepared for EPRI by NUS Corp. of Rockville, Maryland, highlights the potential growth in foreign uranium production. A greater diversity of supply would provide insurance against the inability of a single supplier to perform under existing and future contracts.

The advantages of going abroad for uranium, however, must be weighed against the reduced reliability of foreign contracts because of the involvement of two or more governments. Moreover, many issues not present in a domestic commercial transaction must be considered.

Until recently U.S. utilities could not, for all practical purposes, use foreign uranium for nuclear power production because of a government limitation on the amount of foreign ore permitted to be enriched at U.S. plants for domestic use. This limitation, however, is gradually being lifted and will probably be completely removed by 1984.

The principal countries examined in the report include Australia, Canada, South Africa, and France. Australia appears to be of major near-term interest. The report notes, "No other part of the world has such large [uranium] resources substantially uncommitted and with such major potential for expansion." Recent negotiations within Australia indicate that the country may become a major world supplier of uranium as early as 1983.

"In recent years the question of uranium availability has become more international in scope and increasingly complex," says EPRI Project Manager Jeremy Platt. "This report is a source book on the numerous issues bearing on foreign uranium availability."

Platt says these issues include reserves, resources, and exploration; production capacity, plans, and prospects; national policies and relevant political and economic conditions; foreign uranium demands; and other relevant factors that have or may have an influence on access to and the price of foreign uranium.

## Coal-Cleaning Site Selected

The Homer City Generating Station near Indiana, Pennsylvania, will be the site of a new coal-cleaning developmental test facility for the utility industry. About $6 million has been authorized for the design, construction, and operation of the coal-cleaning plant, which will be capable of cleaning 4–20 t/h of several domestic coals, particularly fine coals.

The purpose of the research effort is to expand the utility industry's use of domestic coals in compliance with the national energy policy. Technology development is scheduled to begin in mid-1980, when construction will have been completed. Researchers will examine and improve several conventional methods and explore new ways to reduce the difficulties encountered in burning high-sulfur, high-ash coals.

The facility will be built on a site owned by Pennsylvania Electric Co. (a subsidiary of General Public Utilities Corp.) and New York State Electric and Gas Co. The owners of the Homer City station and the Empire State Electric Energy Research Corp. are joining EPRI in sponsoring this project, which will be managed by EPRI.

"There are nearly 500 commercial coal-cleaning plants in the country today, but up to 20% of the raw coal's energy-producing potential is being rejected," reports EPRI Project Manager Kenneth Clifford. He adds that some of the coal-cleaning methods to be investigated at the Homer City facility will ultimately enable utilities to burn coal and meet environmental standards without high energy losses.

In addition to environmental reasons, coal cleaning improves the reliability of boilers by removing the contaminant minerals that corrode and erode equipment.

The conceptual design of the facility was developed under EPRI contract by Birtley Engineering, a division of Sverdrup & Parcel and Associates, Inc.

Kaiser Engineers, Inc., has been selected for the preliminary engineering and construction work on the project. GAI Consultants, Inc., will assist with permit applications and environmental requirements.

# Washington Report

**Passive solar energy is receiving increasing federal attention as a viable option for reducing the energy requirements of buildings.**

Formerly slighted by those more interested in active solar technologies, passive solar is moving out of the shadows of public neglect and into the limelight. For example:

▫ Passive solar was identified by DOE as one of eight top candidates for commercialization.

▫ It received substantial support during regional public hearings held as part of the cabinet-level Domestic Policy Review on Solar Energy announced by President Carter on Sun Day, May 3, 1978.

▫ It was the subject of congressional hearings before the House Subcommittee on Advanced Energy Technologies and Energy Conservation last fall and was singled out for favorable comment in a report prepared by the House Commerce Subcommittee on Oversight and Investigations.

▫ At the eleventh hour, it was deemed eligible under certain circumstances for the solar tax credits provided by the National Energy Act.

▫ It received a boost toward commercialization from the Department of Housing and Urban Development (HUD) with the award in December of $1.4 million in grants for the design and construction of 242 homes using passive solar energy.

### A function of design

Passive solar is as much a function of architectural design as it is an energy conservation technology. A passive solar building is one that uses design characteristics, such as large, south-facing windows, glazing, and insulation, and natural forces, such as radiation, to collect, transfer, store, and distribute solar energy for heating and cooling. Active solar systems, on the other hand, use mechanical equipment, such as collectors, compressors, pumps, and fans to transfer the sun's energy.

The two types of systems are not incompatible. Said Joseph Sherman, director of HUD's Division of Energy, Building Technology, and Standards, at the passive solar energy hearings last fall, "These two types of systems should not be considered separately or in competition with each other; instead, we believe that good solar design has three steps—energy conservation, effective passive solar design, and where appropriate, an active solar system."

Although builders, architects, and homeowners will be the parties most directly concerned with passive solar, electric utilities are interested for a number of reasons. Passive solar has the potential to reduce the energy demand of buildings, thus affecting a utility's future need for capacity expansion. In addition, passive systems, like active ones, may require electric backup during extended periods of cloudiness. EPRI and Pacific Gas and Electric Co. are cosponsoring a project to monitor a passive heating and cooling system on a new home in Stockton, California, to help utilities and their customers identify the best ways to combine passive solar with today's electric systems.

### Developing the technology

The list of those involved in the development of passive solar energy is extensive and includes:

▫ Congress, which in 1974 passed the National Solar Heating and Cooling Demonstration Act establishing a solar demonstration program in HUD. The program, now in its fifth and final cycle, has funded the purchase and installation of solar energy equipment in thousands of residences across the United States. Projects have primarily involved active systems, but interest has been building in passive.

▫ HUD, whose Division of Energy, Building Technology, and Standards exercises prime responsibility for the solar demonstration program. "HUD's efforts are directed toward encouraging the housing industry to install and market solar heating and cooling systems," Sherman stated. The agency also collects data on performance, market acceptance, and system maintenance.

▫ DOE, whose Office of Conservation and Solar Applications conducts R&D on passive solar and provides funding for HUD's demonstration projects. According to a DOE draft of a commercialization strategy report on passive solar energy, the agency has constructed and instrumented 29 building experiments and test cells to help overcome barriers to passive solar acceptance. Design tools and computer programs are also being developed.

□ Solar Energy Research Institute (SERI), the leading national laboratory for providing technical and management support to the national passive program, hosted the technical and market evaluation of design applications for the HUD passive design competition last year.

□ Regional Solar Energy Centers, which will help coordinate passive solar commercialization activities with state and local offices, according to testimony before the House subcommittee by Omi Walden, assistant secretary for DOE's Conservation and Solar Applications. She commented that workshop and other information dissemination activities are specific instances where the regional centers will be involved.

**Passive not new**

Passive solar energy is not a new idea. Passive advocates point out that years ago the Pueblo Indians of the Southwest used adobe to provide climate control, a form of passive solar application. During congressional testimony, HUD's Sherman referred to solar homes advertised in the 1950s that were essentially passive in nature. "These early 'passive' homes lacked the sophistication that has now been developed," he noted. "Designers did not really understand the mechanisms available to store energy, and there were no objective and effective methods to calculate the solar energy received and used to meet the building's energy demand."

As a result, the passive energy approach to building design has not received wide application. Although Walden has referred to DOE estimates of approximately 500 buildings using passive solar energy in existence today, other estimates put the number lower. Most existing buildings are custom-built because "few builders have been willing to construct speculative [for sale on the open market] solar homes," said Sherman.

DOE's draft of its commercialization strategy report lists three obstacles to widespread use of passive solar—a lack of understanding and awareness of passive solar heating and cooling by the building community, a lack of quantitative basis for the design of passive systems, and a lack of understanding of the economics of passive solar heating.

Only recently has DOE-supported research provided objective analysis techniques that enable builders, designers, and homeowners to calculate the contribution of a passive solar system to a building's energy demand. The availability of these techniques, together with a growing interest in passive, led to HUD's Passive Residential Design Competition and Demonstration Program. Vivian Loftness, project manager for passive solar with the American Institute of Architects Research Corporation (HUD's technical adviser in the solar demonstration program), calls the design competition the turning point for passive solar. The competition resulted in the award of 145 grants of $5000 each for the design and construction of new passive homes and 17 awards of $2000 each for designs involving retrofit of existing buildings. Significantly, of the 145 awards for new homes, 80 were for one or more units built for sale on the open market.

**Commercialization**

DOE's draft commercialization strategy report is optimistic about the commercial potential of passive solar. "The potential for early commercialization and significant energy impact is high because many passive solar approaches are cost-effective in every part of the country," it states. The document cites buildings in New Mexico, New Jersey, and California with fuel bills under $100 for the entire heating season, well below those of conventional homes in the same neighborhoods. Claiming that passive solar elements reduce energy use by an average of 50% for new single-family residences, the report puts the cost of passive solar building elements between $2000 and $8000. Loftness estimated the cost of the system as $8000–$10,000 per house but said the cost "can become with time easily incremental to the building's design and construction." In testimony during hearings last fall, she continued by stating, "The integral nature of a passive heating and cooling system with the building will allow the economics of conventional construction to bear most of the load. . . . The use of conventional building materials and construction skills allows for immediate application."

Passive solar advocates also say that reliability and performance characteristics are favorable to commercialization. Michael Holtz, chief of SERI's Passive Technology Branch, testified during the congressional hearings that high reliability results from the use of common building materials and construction techniques, few moving parts, and moderate operating temperatures.

**Education is cornerstone**

Walden's testimony emphasizes that the commercializable items of passive solar are the designs and design process and the products and assemblies. "These can be commercialized through a comprehensive program to stimulate the development of cost-effective materials, components, assemblies, and systems through research, development, education incentives, and other activities."

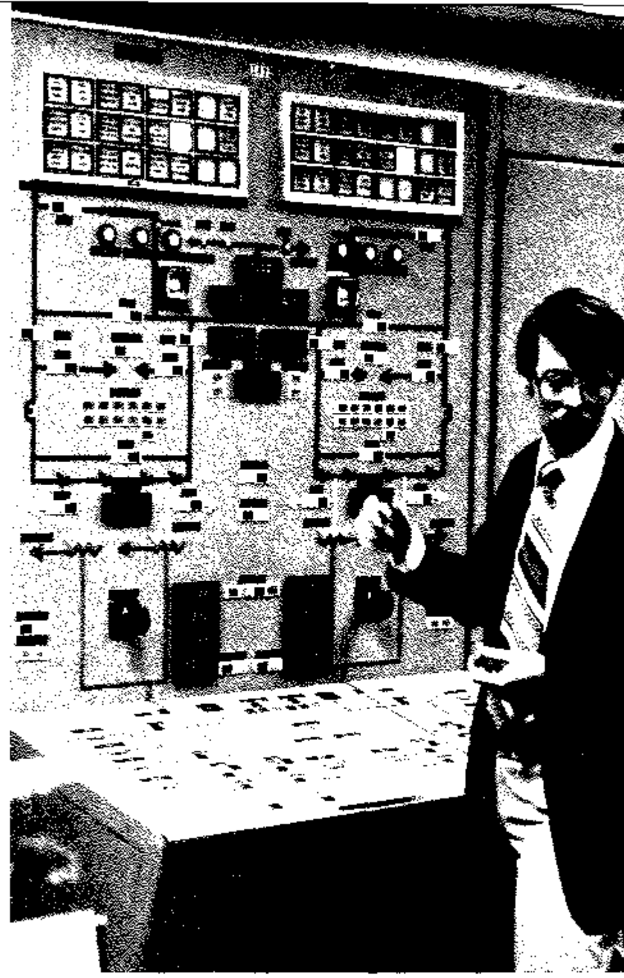
She stresses that education and information dissemination form the cornerstone of commercialization. "Education of the consumer will stimulate demand for passive solar systems. Education of the key participants in the building industry (designers, builders, developers, lenders) and the expansion of existing professional design and trade organization programs will greatly stimulate near-term use."

Loftness also emphasizes the importance of a systematic education program and named the architectural profession as a potential channel for transferring passive solar design concepts to the building industry and eventually to consumers. Quoting Herbert Epstein, vice president of AIA, she told the House Subcommittee on Advanced Energy Technologies, "Architects have a crucial interest and role to play in the application of solar energy . . . in buildings. Just as every law must begin with a legislator's draft bill, every building must begin with a decision. It is at that point that the decision to use solar energy should be made."

# New Controls for Reactive Power

by John Marks

**Skilled application of modern thyristor technology offers utilities smooth, closed-loop control of reactive power flow. The system in Duluth, Minnesota, afforded a focal point for information exchange.**



Mike Bahrman, responsible for the operational performance of Minnesota Power & Light Co.'s Square Butte HVDC link, explains the operator's control panel at the Arrowhead Converter Terminal.

In addition to furnishing real power, all electric utilities must furnish reactive power throughout their systems. Because demand changes sporadically, as well as in daily and seasonal cycles, special devices are needed to switch a supply of reactive power (volt-ampere-reactive, or VAR) in or out of a circuit.

Reactive power, of course, is derived from shunt capacitors, shunt reactors, and series capacitors. These are usually switched in and out of a network in small increments as conditions vary. Larger banks may be switched in or out quickly by voltage-sensing control devices after large system disturbances.

Smooth and even faster control of reactive compensation in exactly the needed amount for transmission systems has long been a goal of power engineers. But until recently no single device could give both smooth and rapid control of bulk VAR flows when needed. Mechanical switches are relatively slow-acting (usually taking a few cycles) and are used to switch large amounts of capacitance or inductance in or out of the system to maintain steady-state conditions within acceptable limits. Use of high-speed switches often results in transients that may precipitate a worse condition than the previously unbalanced reactive power flow. And although synchronous condensers (the only other alternative) are smooth, their response is still not fast enough. Further, their high cost, high maintenance, and low reliability discourage their use.

The best of both worlds—speed and smooth, effective action—arrived with the acceptance of solid-state thyristor switches. These were first applied by utilities as control valves for dc converter terminals; before that, they were widely applied by industry to control flicker caused by arc furnaces. Now they are being used to control the fast, smooth flow of VARs on utility systems. Thyristors can be triggered in less than one cycle; in fact, their principal attribute is their ability to fire at a particular time in each half-cycle. They are fast, easily triggered in a smooth action, and have proved reliable as high-power devices in dc applications, as well as in industry.

### Static VAR generator systems

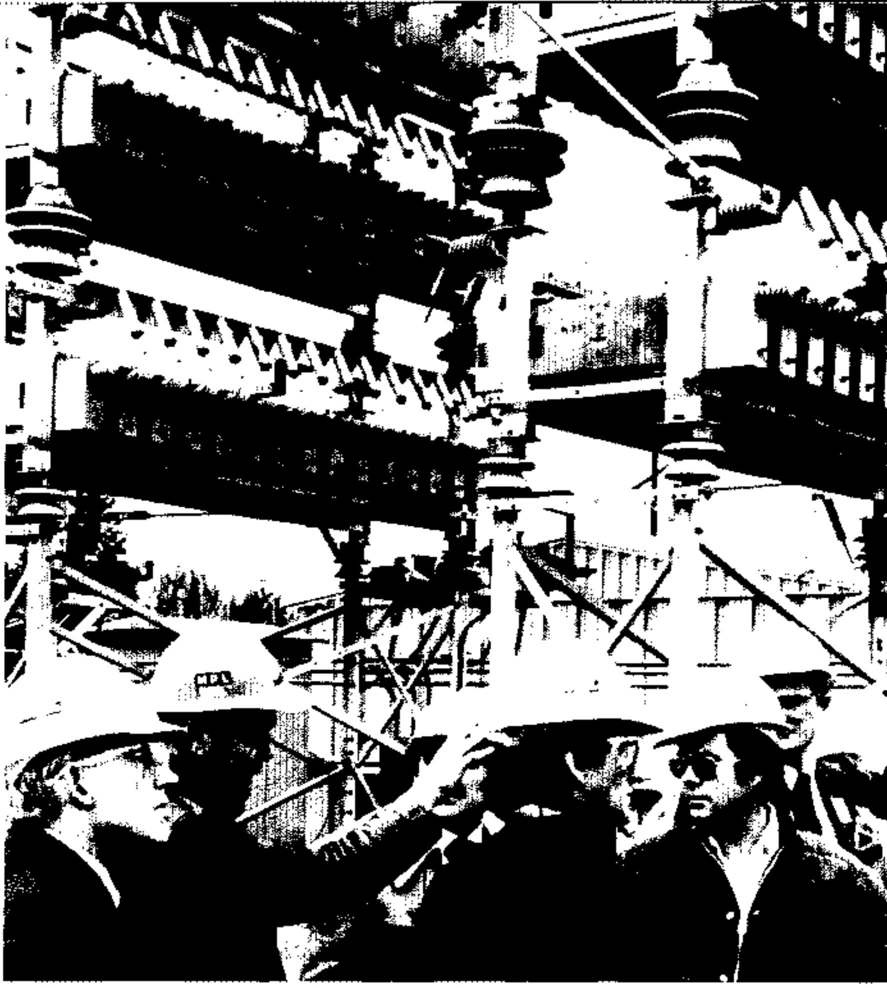
Strictly speaking, static VAR generators (SVGs) that use thyristors to control power flow do produce small, steplike changes in the amount of reactive compensation. But the increments of change are so small and frequent (every half-cycle) that for all practical purposes they appear as continuous adjustments. Hence, an SVG system provides the continuous adjustability of the synchronous condenser with the high reliability and low maintenance associated with static capacitors and reactors. Added to this is rapid response afforded by thyristor technology as demonstrated in modern HVDC transmission systems.

The application of capacitors, reactors, and synchronous condensers is a mature subject with which system planners and operators are familiar. But application of static VAR generators for compensation on system networks is not as well understood because the SVG is a relatively new form of compensation. SVGs have been in use for approximately a decade, but most have been applied to control voltage flicker caused by a large industrial load, such as an arc furnace.

### Information exchange

One of the first applications of solid-state thyristors to initiate and control VAR flow on

John Marks is technical information coordinator in EPRI's Electrical Systems Division.



Fred Nylander, project engineer for the Shannon Substation static VAR generator, describes performance of the 36-MVAR capacitor bank to a touring group of seminar attendees following the Duluth conference.

a transmission system in the United States was by the Minnesota Power & Light Co. Hence, a seminar was convened in Duluth in October 1978 to exchange information and to allow utility personnel to inspect an operating system. Cosponsored by EPRI and MP&L, the seminar sparked discussions on the different viewpoints of users and suppliers.

A major objective of the seminar was to develop the basic principles and benefits of proper SVG application to enhance system stability. The principal question addressed was the type of SVG system to use. Basically, four types of SVG systems using thyristors are available. Three of them simply control a capacitor bank, a reactor bank, or both in combination. The fourth consists of a saturable reactor, which is designed to maintain the power frequency voltage at a set level.

Since the technology is so new and experience is limited, a consensus on the best system to use could not be drawn at the seminar because the conditions of application were not known. However, more than a simple review of the state of the art took place, as each control system was thoroughly discussed. (A copy of the proceedings of the seminar is available from EPRI.)

### SVGs on MP&L's system

MP&L's use of the SVG is part of a research project initiated in 1976 by EPRI, which involved installation of such a unit on part of a utility transmission system. The project covered development, design, and installation of a 40-MVAR, thyristor-controlled reactor in parallel with two 35-MVAR shunt-capacitor banks to control the 115-kV transmission voltage. The research was to evaluate the SVG's performance over a range of conditions, as well as to develop and evaluate suitable closed-loop control.

The MP&L system is particularly suited to evaluate fast, static voltage support and control. Iron ore processing, the major industry served, accounts for 48% of total system demand. The high growth rate of this segment of MP&L's load is responsible for some of the system problems that may be solved by the SVG. The mining load is projected to grow from 284 MW in 1976 to 684 MW in 1979 and may surpass 1200 MW by the mid-1980s.

The load on MP&L's system consists mostly of induction motors and synchronous motors with noncontrolled excitation; both are used in taconite production. The SVG has successfully corrected fast, minor voltage excursions that occur during motor starts. Although switched capacitors could also be set fast enough to respond to motor-start disturbances, the capacitor block size would have to be small to provide a level voltage profile. Unfortunately, the frequent operations necessary for such an arrangement would soon cause a conventional switch to fail.

The greatest need on the MP&L system is for voltage support provided by capacitors or leading VARs. A shunt-connected, fixed capacitor bank in parallel with a thyristor-controlled inductive reactor is basically the SVG that MP&L has installed for close voltage control on a small part of its transmission system. The SVG replaces one large, mechanically switched shunt capacitor previously used at transmission voltages to counter disturbances.

### Principles of operation

The current in the reactor on the MP&L system is controlled by the firing angle of the thyristor switch, which determines the conduction angle in each power half-cycle. As the firing angle, measured from the peak of the applied voltage, is increased from 0° to 90°, the conduction interval is reduced from maximum (full inductor current rating) to zero. Thus when the capacitor and inductor ratings are equal, the SVG can present a continuously variable reactance in each phase, ranging from zero to full capacity of reactance.

An important feature of the device is the speed at which the effective impedance can be changed. The system voltage is measured by the control circuit, varying each half-cycle, and compared with a referenced voltage. This provides an error signal that serves as a basis for determining the firing angle in the next half-cycle. This process is repeated each half-cycle so that the compensator responds very rapidly to voltage changes in the system.

### What the future holds

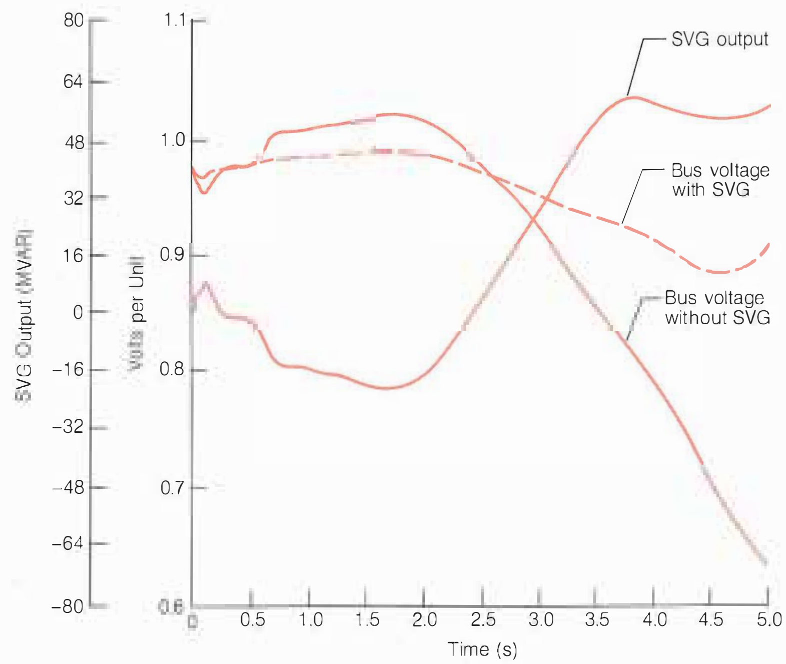
In Canada, five dynamic compensators (capacitive) rated 300 MVAR each will be installed by Hydro-Quebec in the near future on transmission lines bringing power south from the James Bay drainage area. As a result of this decision, the number of 735-kV circuits required to transmit 16 GW will be reduced from 16 to 10.

As transmission systems become more heavily loaded, there will be greater need for fast-response compensation to improve stability margins and to provide voltage support. Static VAR generators could be expected to:

- Increase steady-state transfer limits of existing transmission lines and improve system stability
- Reduce system oscillations caused by short circuits, loss of load, of generation, or of transmission
- Control steady-state system overvoltages caused by line switching
- Control VAR flow to reduce system losses and line loadings
- Support system voltage when switching large loads
- Reduce voltage flicker caused by rapidly changing loads (an electric arc furnace, for example)
- Correct voltage phase imbalance
- Support system voltage levels during a transient swing to maintain synchronism

Each application of the static VAR generator is different, and it is necessary to make a careful study of the specific problems of the system to which it will be applied. The SVG has already proved a highly effective and reliable compensator in arc furnace installations, which gives assurance that application to transmission lines will also be effective and will result in high reliability and low maintenance.

Calculated voltages, plotted for system conditions with and without the static compensator, show the improvement expected from using the compensator.



# R&D Status Report
# FOSSIL FUEL AND ADVANCED SYSTEMS DIVISION

Richard E. Balzhiser, Director

## BATTERY COMMERCIALIZATION

*Commercialization is the process of turning a concept into a product. Proving the technical and economic viability of a technology, such as batteries, is a prerequisite for achieving commercialization, though not an assurance that it will take place. In fact, most failures to commercialize (88% according to one study) result from nontechnical problems, such as market barriers, financial constraints, and management failures (by the developer). Within the Energy Storage Program, a concerted effort is being made to ensure that batteries will become commercial products for electric utility service.*

Battery energy storage systems are being developed to offer the electric utility industry an option for peak period power availability that is not petroleum-dependent. EPRI's battery subprogram focuses on two technologies:

▫ The zinc-halogen battery (RP226 and RP635), with primary emphasis on a $19 million, 4½-year effort by EPRI, DOE, and Energy Development Associates (EDA) to build a 5-MWh zinc-chlorine battery for test and evaluation at the Battery Energy Storage Test (BEST) Facility. EDA is a wholly owned subsidiary of Gulf+Western Industries, Inc.

▫ The sodium-sulfur battery (RP128), being developed under a $17 million, 3½-year EPRI–General Electric Co. effort to build and test seven 100-kWh sodium-sulfur batteries, containing a total of about 3000 cells. Results will permit projection of product reliability and factory cost and will be the basis for fabrication of a 5-MWh prototype to be tested at the BEST Facility.

When projects reach this size—which is characteristic for the engineering development phase—it is insufficient to address only the technical and engineering issues. New questions arise: What performance, reliability, and durability must be demonstrated before utilities will commit to purchasing batteries? Do utilities represent a real and continuing market for battery energy storage? Which utilities will be the first to purchase batteries? Who will supply the basic technology and who the auxiliary systems and components? What obstacles are likely to arise in commercialization of advanced batteries? How will initial high-cost systems be funded? Who will underwrite the learning curve and product warranties? The answers to these and related questions have a significant influence on how a technical project is planned and conducted—what the milestones should be, who should perform the work, how much supplier cost-sharing is appropriate, and how much utility involvement is required.

### Development: corporate participation

Two key requirements for ensuring that technology development projects are on the road toward commercialization are corporate cost sharing and business planning. Cost sharing ensures top management's continued interest and review, permits the manufacturer to maintain patent positions, and ensures the highest possible level of funding for R&D, testing, and evaluation with a view to commercialization. Two major EPRI battery contractors, Gulf+Western and General Electric, are committing about $5 million each to the present 3–4-year projects; this represents approximately 30% of the total funding.

Business planning involves establishing a logic and a schedule that can guide and integrate development and commercialization. It means evaluating market viability, determining capital and commercialization requirements, scheduling manufacturing capability, selecting component and material suppliers, identifying R&D needs, and assigning corporate responsibilities for development, marketing, and commercialization activities. For example, this year General Electric's sodium-sulfur battery project has been transferred from the firm's Corporate Research & Development to its Power Systems Sector—familiar to the utility industry as a supplier of all types of generation, transmission, and distribution equipment. Thus, the relevant sectors of General Electric are now becoming engaged not only in the development but also in the marketing and commercialization of the sodium-sulfur battery. Similarly, EDA is now involving parts of its parent company as well as pump, motor, material, and component suppliers in the planning and conduct of zinc-chlorine battery development.

### Demonstration: the utility interface

The emphasis on commercialization has resulted in the planning and integration of two battery demonstration projects. The first of these is the $14 million BEST Facility, which is being built and will be operated by Public Service Electric and Gas Co. for DOE and EPRI. The second is the $10 million–$20 million Storage Battery Electric Energy Demonstration (SBEED) plant, for which a cooperative agreement between DOE and a host utility is expected to be signed this year. Utility participation and the battery-utility interface are key aspects of both projects.

The BEST Facility will be a national center for testing 5–10-MWh advanced battery systems in the early 1980s in modes of operation that can be anticipated for commercial units. The primary purpose of the facility is to provide data on advanced battery system operation to minimize the technical and economic risks in moving the technology from development to commercialization. Although the emphasis is on evaluation of prototypical technology, battery testing in BEST will be conducted on a scale and in modes that are more representative of a utility than an R&D environment.

SBEED will be conducted in a fully operational commercial-size plant, substantially larger than the BEST Facility. The plant will use conventional lead-acid batteries, will employ utility operators and maintenance workers, and will respond to actual load demands. Startup is scheduled for 1983. The main purpose of this demonstration is to achieve an early resolution of power system questions relating both to battery impacts on system planning and operation and to the interaction issues vital to market acceptability of dispersed battery storage technology. Of special interest is the study of battery interaction with the power system in terms of controllability, dynamic response, harmonics, resonance, and augmentation of frequency stability. Once the SBEED plant operates as an integral part of the power system, the worth of the battery to the utility industry can be calculated for planning purposes by evaluating such parameters as production cost and spinning-reserve savings, cost savings from deferral of T&D line installations, deferral of penalty of limited energy output, type of construction, lead time for installation, environmental compatibility, and flexibility of siting.

Achieving the objectives of BEST and SBEED should generate the confidence to proceed with the next step in commercialization. Defining exactly what constitutes success with these projects is, however, a major issue. What information do buyers need before they commit to purchasing batteries? Only utility industry representatives can make decisions on this and related uncertainties, such as the benefits of battery energy storage and the definition of appropriate battery specifications. EPRI is establishing a Battery Users Group to address these questions. This group of utility representatives will include personnel from the operating, system planning, engineering, and financial sectors.

### Underwriting the learning curve

Once the battery technology issues have been successfully addressed by BEST and the power system issues resolved by SBEED, the primary barrier remaining will be manufacturing costs. The issue is, who will underwrite the cost of a manufacturing facility and the high costs of initial battery systems? A learning process is required to achieve a lower, more acceptable cost for batteries, and the initial, higher-cost batteries will have only a small market. The market projections for 1985 range from 10 MW/yr ($450/kW) to 2000 MW/yr ($300/kW). A market size of 200–400 MW/yr is the minimum necessary to justify the investment required for the production plant. It appears that private industry will be able to make the required investment (estimates range from $15 million to $30 million), provided that it can be assured of a market for its product. The utilities will provide the market if the product is available at a reasonable price and with a commercial warranty. It appears that government financial assistance may be required to bridge the gap between the two, either by subsidizing the cost of moving down the learning curve or by assisting the manufacturer in guaranteeing performance.

One approach to subsidizing the cost of moving down the learning curve for lead-acid batteries has been suggested in a recent study by Arthur D. Little, Inc. (ADL). This study concluded that creating a demand was more difficult than creating a supply; therefore, the proposed subsidy should go to the buyer (the utility) rather than directly to the supplier. In order to appropriately plan the subsidy program, ADL identified the main concerns utilities have about purchasing battery energy storage systems:

- Reluctance to accept spinning-reserve credit
- Reluctance to accept a credit that would result from a fuel cost escalation rate that is higher than the general rate of inflation
- Difficulty of justifying capital-intensive technologies and of obtaining access to capital markets

The basic principles of the ADL approach are (a) that the federal government should purchase a limited number of load-leveling battery plants and lease them to the utilities to overcome the third concern and (b) that the leases should be subsidized to overcome the first and second concerns about credits. Assuming successful completion of the program, the leases would be sold and the government reimbursed for its investment. Theoretically, this approach could be used for any battery that successfully completes BEST testing. Other approaches being studied for commercialization of batteries and other technologies include direct loans, loan guarantees, tax incentives, and warranties. An EPRI project to evaluate incentives and commercialization scenarios for batteries has been approved and will soon be undertaken. A major objective of this project is to determine the impact that commercialization planning has on the direction of EPRI's RD&D program.

In addition to financial incentives, policy incentives are important to the commercial success of battery energy storage. For example, regulatory commissions could adopt policies that would encourage purchase of high-risk technologies, such as batteries, that would be of national benefit (e.g., technologies that would have beneficial environmental impact or encourage use of domestic fuels). To date, the practices of most regulatory bodies tend to discourage purchase of capital-intensive, high-risk technologies.

### An integral part of R&D

The commercialization of a new product does not happen overnight; nor is it a simple step that automatically follows research, development, and demonstration in an orderly and predictable fashion. It is a process that permeates the entire RD&D program, beginning with technoeconomic feasibility studies and market analysis during the R&D phase, continuing with substantial user involvement and evaluation in the demonstration phase, and in the final state, bringing together the potential supply and potential demand in a free-standing market. In this sense, EPRI's Energy Storage Program is integrating commercialization activities into the planning and implementation of the battery R&D program. *Project Manager: James Birk*

## COAL SLURRY FUELS

*It may be possible to fire some utility boilers designed for oil combustion with fuels made of mixtures of pulverized coal (PC) and a carrier liquid. The development of this technology could reduce the U.S. electric utility demand for imported fuel oil.*

The electric utilities in the United States are being compelled to decrease their reliance on the use of imported fuel oil because of high cost and instability of supply and because of federal oil and gas prohibition orders. As a result, there is increasing interest in converting oil-fired power plants to coal operation.

### Boiler conversion

Two categories of boilers are thought of by some as potential candidates for conversion to direct PC firing: coal-design boilers, which were originally designed to burn coal but have been converted to burn oil exclusively, and oil design boilers, which were designed to burn oil only.

Because modern boiler design reflects the type of fuel to be burned, the conversion of an oil-design boiler to total PC operation is impractical and uneconomic. Coal often contains up to 1000 times the ash content of residual fuel oil, and during combustion this ash becomes molten and sticky. The combustion products containing the ash must be cooled sufficiently before entering the boiler convection sections to limit slagging. Coal ash is also a highly abrasive material, and to limit the erosion of boiler tubes, the velocity of the gases coursing through the boiler must be limited to well below that of oil combustion products. Because of these problems with high ash content, a coal-design boiler has to be significantly larger for a given output capacity than an oil-design boiler. This means that an oil-design boiler converted to coal will operate at a severely reduced maximum output capacity, typically only 50% of the original oil-design rating.

The large quantities of ash produced in PC-fired boilers must be continuously removed and disposed of. This requires the use of steep boiler-hopper bottoms, ash pits, electrostatic precipitators, and ash-conveying systems that are not required for oil-design boilers. The preparation of PC for combustion is a complicated process requiring highly specialized machinery, whereas fuel oil requires very little preparation. Large amounts of land are required to accommodate the equipment needed to process the coal and ash—land that is often unavailable near existing oil-design power plants. The capital cost of converting oil-design boilers to coal operation is high, typically approaching the cost of a new coal-design unit of equal capacity.

Besides the direct capital costs of conversion, there are also the costs of providing replacement electricity while the unit is shut down for conversion and the loss of generating capacity due to derating. In view of all these disadvantages, there is little incentive to convert a unit from oil to coal operation.

The coal-design boilers that have been converted to exclusive fuel oil operation are capable, by the nature of their design, of being reconverted to 100% coal operation but are often beset by other site-specific obstacles to reconversion. The most important of these obstacles is the condition of the fuel preparation, ash disposal, and coal combustion equipment. If these facilities were dismantled when the unit was decommissioned from coal operation, then replacement with new equipment at high capital cost is required. Many coal-design units were converted to oil operation to comply with increasingly stringent emission regulations. The reconversion of these units to coal operation will usually necessitate the replacement of the electrostatic precipitators with components that are more modern and efficient and will commonly require the addition of stack gas scrubbers to comply with sulfur dioxide emission standards.

A substantial amount of capacity in the United States falls into this category. The Federal Power Commission (now part of the Federal Energy Regulatory Commission) found that in 1972 nearly 30 GW of capacity, mostly on the East Coast where there is easy access to ocean and river barge transport, had been converted from coal to oil. It was learned that just over half of this capacity could be reconverted to full coal operation within three weeks in an emergency situation. Reconversion of the balance of capacity would require more than one year.

EPRI is pursuing a wide range of technologies that would permit the simplified use of coal in these two categories of boilers. The firing of slurry fuels made from mechanical mixtures of PC and a carrier liquid is considered to be one method of achieving this end. If such fuels were manufactured at central production plants, distributed through existing fuel oil networks, and made commercially available to geographically diverse power plants, many of the debilitating problems of coal utilization in these plants could be overcome. The two fuels under consideration are coal-oil mixtures (COMs) and highly loaded coal-water slurries.

**Coal-oil mixtures**

COMs have been investigated for over a century with generally encouraging technical results, but they have never been commercialized because there has been no economic advantage in using them.

Some attractive features have led to recent resurgence of interest in COMs. Retrofitting COMs to a power plant would involve short downtime and comparatively low capital cost because there would be no need for purchasing new or for renovating old coal-handling equipment. Detailed retrofit criteria and cost estimates for COM conversion in typical power plants are being developed for EPRI (RP1455-2). The results of this project will be consolidated in a handbook for use by electric utilities in evaluating the applicability of COMs to specific power plants.

A COM production and distribution infrastructure could be developed in the near term because extensive new technology development is not required. However, it is doubtful that COMs could take the place of much imported fuel oil in the event of foreign oil embargoes against the United States unless the production and distribution network already existed.

The Power Plant and Industrial Fuel Use Act of 1978 includes provisions to exempt power plants from coal conversion orders if the plant either is using or intends to use COMs.

The Environmental Protection Agency (EPA) does not intend to consider the conversion of a boiler to burn COMs as a major modification. The implication is that units that are converted to use COMs will not be subject to EPA's proposed Standards of Performance for New Stationary Sources. Several important issues remain unresolved, however, that inhibit the implementation of COM use.

The cost of commercial, centrally produced COMs is still largely speculative, and the economic incentive to convert to COM use remains unpredictable. EPRI is sponsoring the conceptual engineering design and economic analysis of a large central production plant to determine probable COM selling prices, to evaluate the market potential of the fuel, and to analyze the various methods of producing it (RP1455-3).

Information is lacking on the long-term utility-scale production and use of COMs. To meet this need, DOE and New England Power Service Co. (Nepsco) are jointly sponsoring the conversion of an 80-MW coal-design boiler at the Salem Harbor generating station to burn COMs prepared on site (Figure 1). EPRI will cosponsor the demonstration phase with DOE and Nepsco. The project (RP1455-1) has four objectives:

- Investigate the emissions produced by combustion of COMs
- Determine if a synergistic effect occurs between coal and oil ash that will aggravate slagging, fouling, and corrosion
- Evaluate the performance of COM pipeline components
- Develop a technique to predict the performance of COMs in oil-design boilers—that is, determine how much an oil design boiler must be derated to use COMs

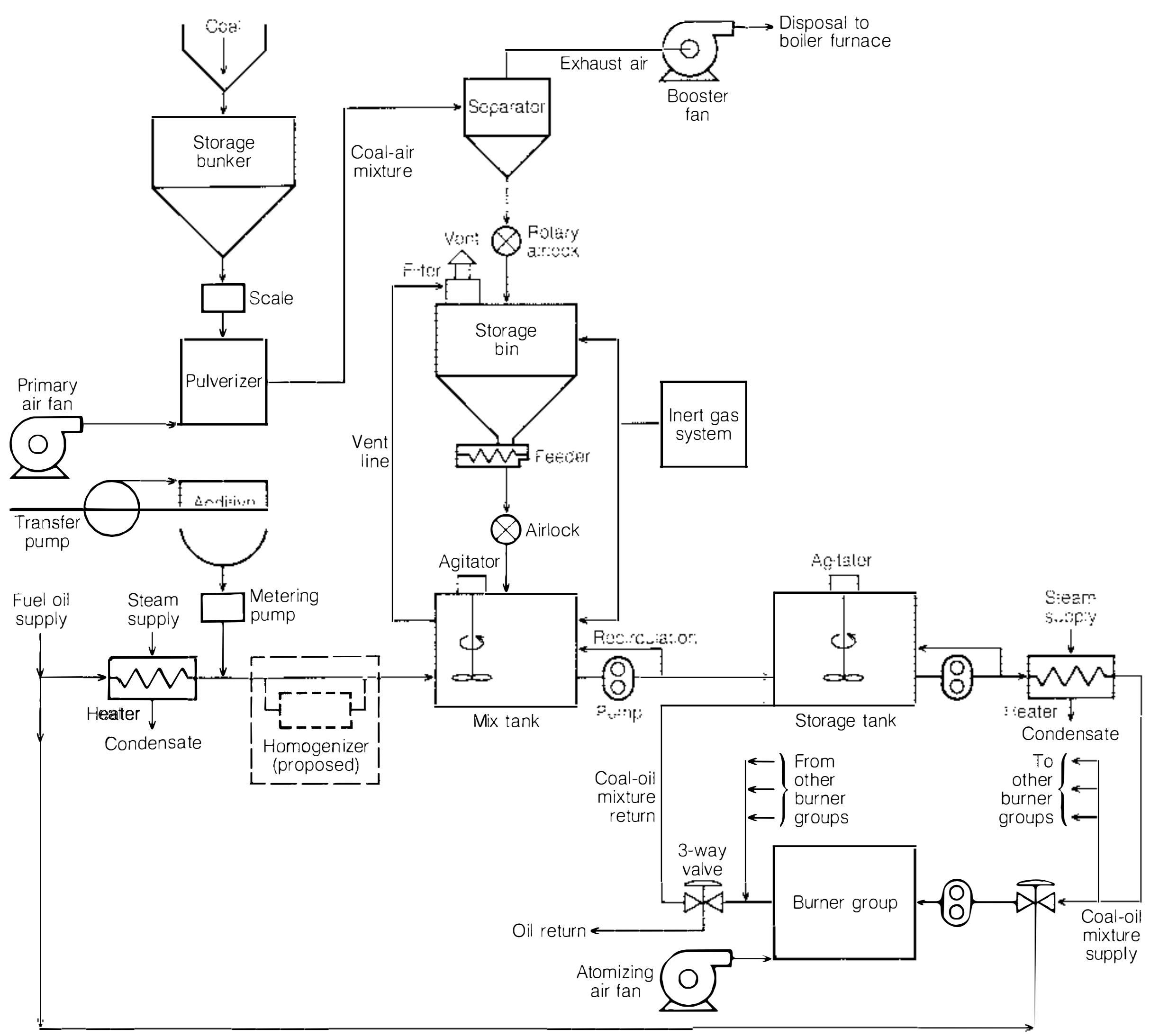
The results of these boiler performance studies will be incorporated into the applications handbook previously described (RP1455-2).

Two previous projects have provided technical support for the work in progress at Salem Harbor. One was an EPRI-cosponsored demonstration of COM use in an industrial package boiler at General Motors Corp., which tested the performance of COM combustion systems (RP527). Unfortunately, the test burns were too short to provide ash damage data and were not conducted at full loads. In the second project, EPRI sponsored a COM stabilizing-additive evaluation program conducted by the University of Massachusetts, which systematically tested the performance of a wide variety of candidate COM additives (RP1030-3). An additive will be mixed with the COM at Salem Harbor to prevent the hard compaction of coal particles that settle out of the mixture.

**Coal-water slurry**

A preliminary scoping study is being conducted by Combustion Processes, Inc., to

**Figure 1 Flow schematic of coal-oil mixture (COM) production plant at the New England Power Co. generating station in Salem, Massachusetts.**




investigate the potential for firing commercially produced, highly loaded coal-water slurries directly in oil-design boilers (RP1180-4). The concept being studied involves use of coals that can be upgraded in quality. The coal will be physically cleaned to <3% ash and low levels of pyritic sulfur and will be chemically cleaned to further reduce ash content and to modify the ash character to decrease slagging and fouling. The development of coal cleaning technology is being sponsored by EPRI in another subprogram. The feasibility of chemical cleaning is as yet unproved.

The coal will be pulverized wet to produce pumpable slurry of 75% solids. The technology to produce such a highly loaded slurry is being developed independently at three organizations: the Atlantic Research Corp., the Colorado School of Mines Research Institute, and the Alfred University Research Foundation, Inc. Texaco uses a highly loaded slurry in its coal gasification process.

Boilers will be modified as required to burn the fuel. A 3% efficiency loss due to fuel moisture content will be accepted, and the boiler will be derated as required to minimize slagging problems but will retain dual fuel capability to operate at full load on oil. *Project Manager: Steven Drenker*

# R&D Status Report
# NUCLEAR POWER DIVISION

Milton Levenson, Director

## STUDSVIK INTER–RAMP PROJECT

*A comprehensive set of tests has been completed on the behavior of typical reactor fuel rods subjected to rapid power changes such as those resulting from some load changes or control actions. Most earlier test results were confused by differences in power history, prior burnup, design, and materials, and by imprecise measurement of power levels. In the Inter-Ramp (I–R) tests, the main parameters were well characterized, and levels of power ramping were well controlled and measured. A strong relationship between the fuel rod failure threshold and the magnitude of power ramping was quantified, indicating dependence on integral effects created during the power history. This work serves as a benchmark for detailed stress-analysis models of fuel rod behavior and provides specific empirical correlations for BWR fuel rods. Similar data for PWR fuel rods will be obtained in a related project.*

The reliability of individual nuclear fuel rods can affect the overall energy-producing efficiency (capacity factor) of a nuclear power plant. This capacity factor can be decreased either if the length of fuel rod service is shortened by serious damage or if regulatory or vendor-imposed restrictions on magnitude or change of energy output (power level) from fuel rods directly reduce the usable energy output of the nuclear plant. Such performance limits for fuel rods have resulted, in recent years, in capacity losses of $\gtrsim$5% in nuclear power plants. Although this may seem a relatively minor effect, it necessitates the use of about $100 million per year of replacement energy (from nonnuclear sources) in the United States alone. However, by implementing current technology in fuel rod fabrication, it should be possible to eliminate most of these capacity losses.

To reach this goal, EPRI is sponsoring studies to establish the relative behavior of both current-generation and modified-design fuel rods during severe power ramping—that is, during rapid power increases that reach relatively high power levels. Such ramping can be characterized by the term power shock, which is a measure of the effect on fuel rods of the change in power from some level representing prior operation to a new, higher level. A fuel rod testing program that includes power shock provides a severe test of the relative reliability of different fuel rod designs: the less susceptible a fuel rod is to damage or failure during a given power shock, the greater its probable long-term reliability. This is particularly true if the power shock occurs after the fuel rods have completed an extended irradiation period.

The EPRI nuclear fuel performance program is now involved in three major projects investigating fuel rod behavior during power shock. All three projects are multiparty international ventures: the Halden Reactor Project (RP216 and RP355), the Studsvik Inter-Ramp (BWR) Project (RP507), and the Studsvik Over-Ramp (PWR) Project (RP1026). Of these three, the second is the nearest to completion, with all major experimental objectives completed. The I–R project is concerned with experimentally establishing the behavior of current-design, unpressurized BWR fuel rods during power ramping. The consistency of the resulting I–R data set provides both an indication that a failure threshold does exist and a detailed experimental basis for analytically investigating the damage and failure mechanisms operating during a power shock condition (using detailed fuel rod modeling codes). The data set also provides a baseline reference for measuring improved performance of fuel rods with modified designs intended to increase reliability.

The I–R project is managed by Studsvik Energiteknik Ab of Sweden and cosponsored by 14 other organizations. The project objective is to investigate the failure propensity and characteristics of 20 fuel rods of typical 8 × 8 BWR design when they are subjected to a power ramp after completing extended irradiations with cyclic power-level variations. Parametric variations in the 20-rod test matrix include burnup ($\sim$10 and $\sim$20 GWd/tU*), fuel-cladding gap size, fuel density, cladding heat treatment (annealed versus cold-worked Zircaloy cladding), and peak ramp power.

The Studsvik R-2 reactor, a high-flux test reactor operated at 50-MW thermal power, was used for both extended and power ramp irradiations of all 20 I–R fuel rods. Five light-water-cooled, natural circulation boiling capsules, each containing 4 fuel rods, were used for extended irradiations, and loops with forced-circulation cooling were used for single-rod ramp tests. Both these facilities simulate BWR coolant temperature ($\sim$293°C; $\sim$560°F) and pressure ($\sim$8.4 MPa; $\sim$1220 psia) conditions.

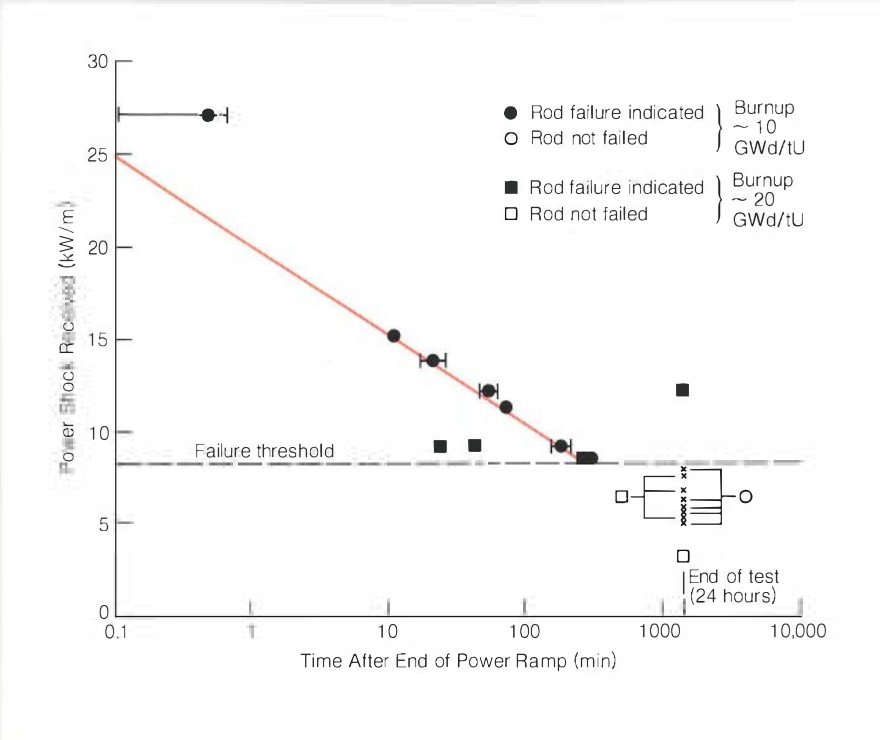
Several features of the I–R project data set significantly aid understanding of fuel rod performance during ramp tests:

- A consistent and highly characterized irradiation environment that simulates BWR conditions
- Detailed knowledge of fuel rod fabrication parameters
- Nondestructive examinations before, between, and after all irradiation phases, and destructive examinations after ramping
- Detailed fuel rod modeling studies conducted by several project participants

The extended irradiation scheme included alternating power cycling, with high-power cycles at peak levels of $\sim$40 kW/m ($\sim$12.2 kW/ft) and low-power cycles at $\sim$25 kW/m ($\sim$7.6 kW/ft). Each extended irradiation started with a high-power cycle and ended

*Gigawatt days per metric ton of original uranium present. One gigawatt day of electric energy could provide a city the size of San Francisco with electricity for about one day.

Figure 1 Relationship between the size of power shock and the presence or absence of fuel rod failure (failure threshold). Irradiation tests were performed on fuel rods that had experienced different levels of power shock (a measure of the severity of a power ramp). At the end of the power ramp, peak ramp power was held for 24 hours, during which time the loop coolant was monitored for indication of fuel rod failure (loss of integrity). After this 24-hour test, all rods were examined to confirm failure or nonfailure.



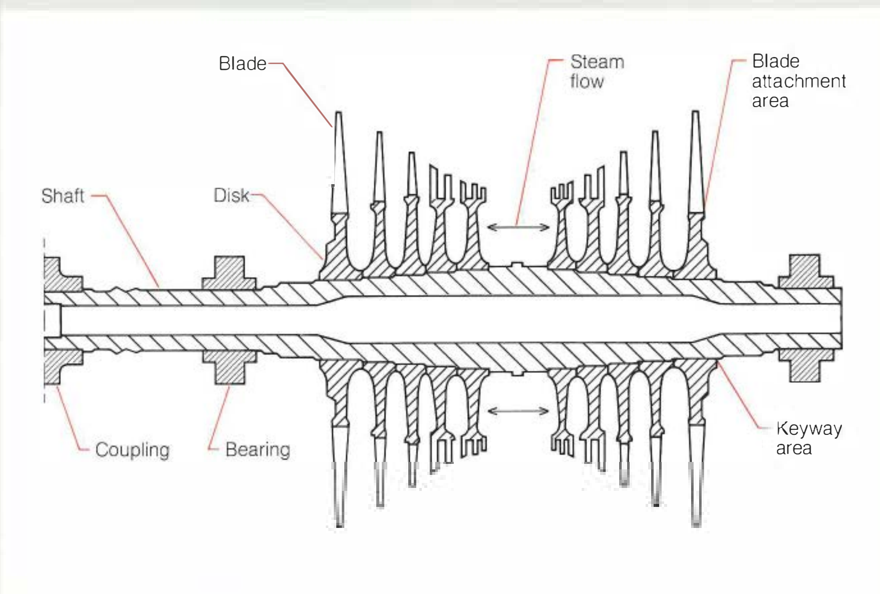




Figure 2 This schematic of a typical low-pressure turbine shows the major rotating structures. The disks are shrunk onto the shaft and prevented from turning during an overspeed incident by means of keys at the disk-shaft interface. Steam enters at the center and exits at either end at a lower temperature and pressure.

with a low-power cycle (with each cycle ~2.5–3.5 GWd/tU in length), continuing to burnup levels of ~10 GWd/tU (12 rods) and ~20 GWd/tU (8 rods). This irradiation produced orderly progressions of fuel rod changes such as cladding creepdown (decrease in diameter due to temperature, pressure, and neutron irradiation conditions), with expected bambooing (minor ridging) occurring at interfaces between adjacent fuel pellets.

The power ramp irradiations, performed between March 1977 and August 1978, produced an almost even split between failures (11) and nonfailures (9). Minor permanent, outward deformation of cladding occurred, with ramp-induced average midpellet and ridging deformations generally less than 0.05% and 0.10%, respectively.

The I–R project data show a strong correlation of both incidence of fuel rod failure and time to failure (indicated by fission-product release to the coolant of the test loop) with power shocks, based on peak ramp power and representative powers selected consistently from each fuel rod's extended irradiation history. The most significant correlation indicates existence of a failure threshold for power shock that separates all failed rods from the rods remaining unfailed after the standard 24-hour hold at peak ramp power (Figure 1). This specific correlation represents power shock based on peak ramp power minus average power during the first high-power period of extended irradiation. It also indicates that high-power operation during the early portion of the extended irradiation period was significant in affecting the behavior of the tested fuel rods during power ramping.

Eight of the 11 failed rods indicated times to failure that appear to be closely related to the magnitude of this same power shock, with time to failure continuously decreasing as power shock increases.

The ramped-power behavior of the I–R fuel rods seems to have no strong correlation with the peak ramp power level, the power level held for the 24-hour period immediately preceding the ramping, the accumulated burnup (for the I–R range of 9–23 GWd/tU), or the variation of I–R project cladding and fuel parameters. *Project Manager: Garry Thomas*

## CORROSION-ASSISTED CRACKING OF STEAM TURBINE DISKS

*The steam turbine is one of the most remarkable devices of modern technology; it produces enormous amounts of power with high reliability. Nevertheless, it is one of the* *leading causes of power plant outage. The most common problems in steam turbines involve control valves, bearings, and blades, all of which can be repaired. However, the less common problem of cracking of major rotating components can lead to significant costs and outages for repair and/or replacement. EPRI is sponsoring two research projects to examine these low-frequency, high-cost events. One addresses the problem of flaws detected during inspection of turbine rotors (RP502). The other, discussed here, concerns low-pressure (LP) turbine disk cracking (RP1398).*

A typical modern LP steam turbine for use in nuclear or fossil power plants is shown schematically in Figure 2. The disks are sometimes manufactured as an integral part of the shaft; other times, the disks, or wheels, are forged separately, shrunk onto the shaft, and prevented from rotating on the shaft during an overspeed by means of keys. One European manufacturer constructs LP turbines by welding disk sections together to form the rotor. Blades are attached to disks by mechanical interlocking; two common types of blade attachments are shown in Figure 3. Shafts and disks are constructed from Ni-Cr-Mo-V, Cr-Mo-V, or similar alloys.

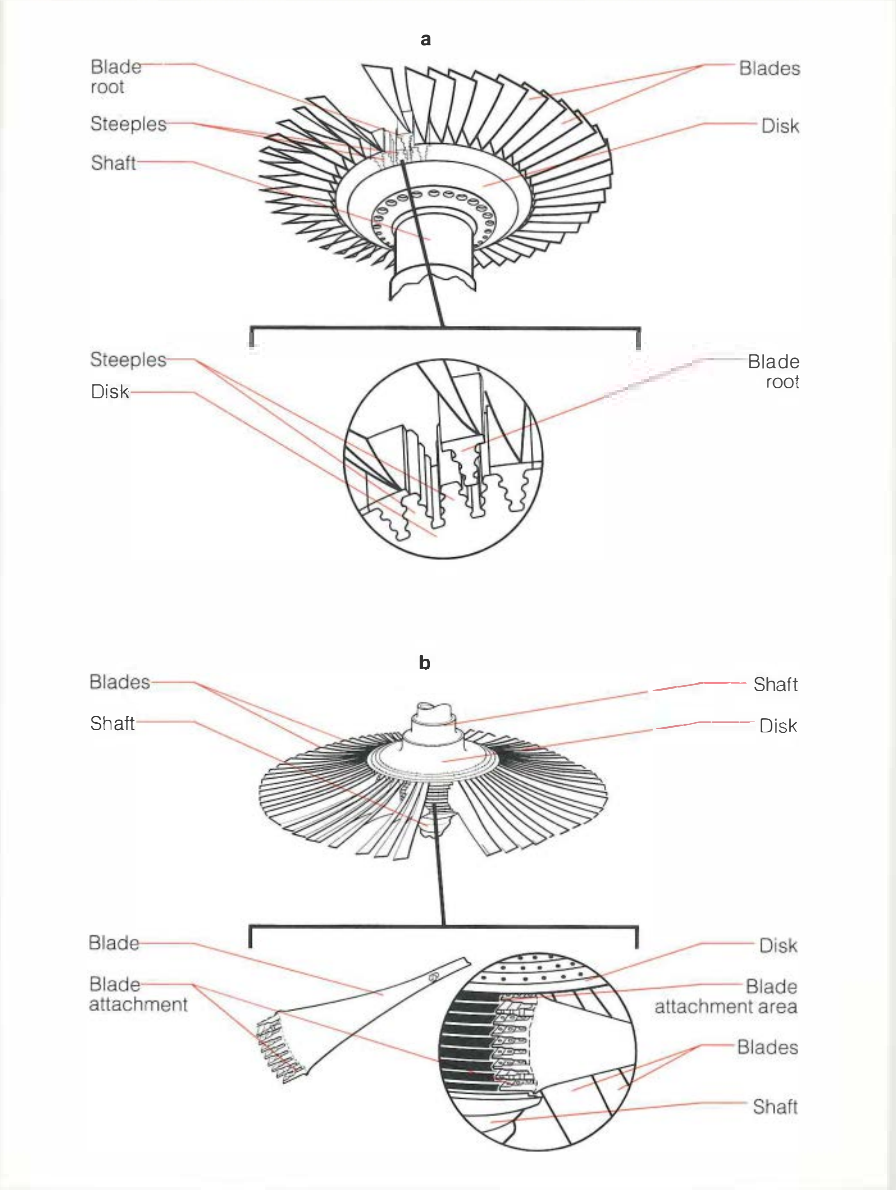
Even very clean steam in units with good control of feedwater purity contains traces of chemical impurities with concentrations in the parts-per-billion range. These impurities are introduced by leaks, system malfunctions, corrosion, or residual impurities in the feedwater. Each of these types of impurity has a unique solubility in steam at a given temperature and pressure. As a result, they condense out of the steam at different positions on a temperature-pressure diagram and, therefore, also in different regions of the turbine. Because of differences in inlet temperatures, inlet pressures, materials, and water treatment, the impurities that condense in a particular region of the LP turbine are different for fossil and nuclear plants.

At full load, the inlet steam temperature of an LP turbine is about 370°C (700°F) for fossil plants and about 260°C (500°F) for nuclear plants; the inlet steam pressure is about 690 kPa (100 psi) for fossil plants and 1380 kPa (200 psi) for nuclear plants. As the steam moves through the turbine, its pressure and temperature drop. At some point, the steam starts to condense on the turbine surfaces. Since the temperature of the turbine parts differs from that of the local bulk steam, condensation on metal surfaces can also occur at locations upstream of the point where bulk condensation begins.

When steam condenses on the metal surfaces of the turbine, it is possible for impurities to reach concentrations many times higher than the concentration in the steam. This effect can be especially pronounced if there is local temperature cycling (alternate wetting and drying) due to load changes or control system effects. Turbine disk cracking can be induced when the presence of locally concentrated impurities and high levels of steady-state stress (stress corrosion) or excessive vibratory stress (corrosion fatigue) is added to residual stresses from assembly and transient stresses due to temperature changes. Turbine disk stresses are determined by the design and manufacturing process and by operating conditions; whether stresses are excessive, however, depends on material properties and the chemical environment in which the turbine operates.

It has been found both experimentally and in the field that certain types of disk materials will crack only at relatively high stress levels in clean steam, whereas cracking will occur

Figure 3 Two common methods by which blades are attached to disks: **(a)** The blade roots are inserted from the side of the disk between adjacent steeples. The blades are retained by the resulting mechanical interlock. **(b)** The blade attachment fingers are inserted directly into grooves in the disk. Steel pins are then inserted from the side of the disk and passed through holes in the disk grooves and blade attachment fingers.



at lower stress levels in steam with significant concentrations of certain trace impurities. Cracking has been observed in the field in all areas of LP turbine disks, i.e., in the blade attachment area, in the disk body, and—in the case of shrunk-on disks—in the keyway at the disk-shaft interface. However, corrosion-assisted cracking usually occurs near places in the turbine where the steam first starts to condense. One region of particular concern is the blade attachment area.

With a few exceptions, in-service examination of disks has consisted of visual inspections with a follow-up magnetic particle inspection when problem areas were observed. Since blades were usually not removed, the blade attachment area could not be inspected. In the last few years, manufacturers and service companies have been working on more sophisticated nondestructive examination techniques for use on disks. One manufacturer has issued a service recommendation for ultrasonic inspection of blade attachment areas and keyways at periodic intervals.

If a crack is found in a disk, maintenance practices require that either the crack be completely removed by grinding or the turbine wheel affected be retired. Fracture mechanics has been used successfully in the gas turbine industry to develop a lifetime prediction for gas turbine parts with flaws of known dimensions and orientations. This analytic prediction can be used to determine permissible intervals of operation of the cracked part before reinspection is required. It is technically possible to extend this prediction method to LP steam turbine disks. However, it is not clear whether a turbine with a known cracked disk could be run routinely in a power plant unless the crack is clearly superficial. The reasons for this uncertainty include questions about: the length of time required between inspections, the stipulations of the utility's insurance company, possible liability of utility personnel who authorize such operation, and possible adverse reactions from regulatory agencies. An additional issue concerns the possible liability of the turbine manufacturer when very complex causal relationships with mixed responsibilities are present.

The goal of this project is to improve and ensure the reliability of LP steam turbine disks. The objectives in attaining this goal are to determine: the causes of disk cracking; the occurrence of keyway cracking in a representative sample of U.S. turbines; and a basis for evaluating under what circumstances, and with what sizes and orientations of defects, useful additional lifetime can be reliably expected. A further major objective is to seek methods for preventing conditions that can cause cracks to initiate and/or grow in size. *Project Manager: Michael Kolar*

## STEAM CHUGGING AND CONDENSATION OSCILLATION

*Chugging is a quasi-periodic phenomenon produced by injection of steam into a pool of subcooled water with subsequent condensation. During a hypothetical loss-of-coolant accident (LOCA), this chugging could induce significant loads on some BWR containments. The phenomenon might also occur, with less severe consequences, in both BWRs and PWRs under non-LOCA conditions. It has received increased attention from both the nuclear industry and the Nuclear Regulatory Commission.*

Early work in this area by General Electric Co.'s licensee in Germany, Kraftwerk Union AG, has contributed much empirical information to overall knowledge of chugging. In this country, BWR owners' groups are supporting programs focusing on the potential engineering and structural phenomena associated with chugging. These programs have led to development of semiempirical correlations that were derived from intermediate-scale or almost-full-scale models.

By contrast, EPRI-sponsored projects are examining the underlying physical effects that produce chugging and the corresponding loads on containment walls. Because of the complexity of the phenomena under study, analytic and experimental investigations had to be carried out simultaneously. This interaction of two projects—analytic modeling at Jaycor (RP1067-1) and experimental studies at SRI International (RP1067-2)—was essential to the success of each of them individually.

In its simplest form, chugging is produced by injecting steam into a vent, which is partially submerged in a pool of subcooled water. The steam generally forms a bubble, or cavity, in the pool and expands to a certain volume. Rapid condensation then occurs, drastically reducing the pressure in the steam bubble. This large pressure imbalance causes the bubble to collapse almost instantaneously, creating pressure waves that propagate through the water until they hit the walls. Repeated collapses (several per second) may cause significant structural loads in the containment.

As data were accumulated in the SRI experiment, it became evident that the Jaycor simplified deterministic models were inadequate because of large fluctuations in the characteristics of the collapsing bubbles. The modeling effort was therefore reexamined. It was determined that chugging must be viewed as an essentially stochastic phenomenon, which requires statistical analysis and modeling. In the current Jaycor model, as the steam-water interface moves outward from the vent pipe, a thin layer of saturated water is formed around it that drastically reduces the condensation rate. However, the motion of the interface creates turbulent eddies. Some large eddies bring cold water to the interface, thus dramatically increasing the condensation rate and triggering the collapse of the bubble. The water rushes back up the downcomer, and another cycle begins.

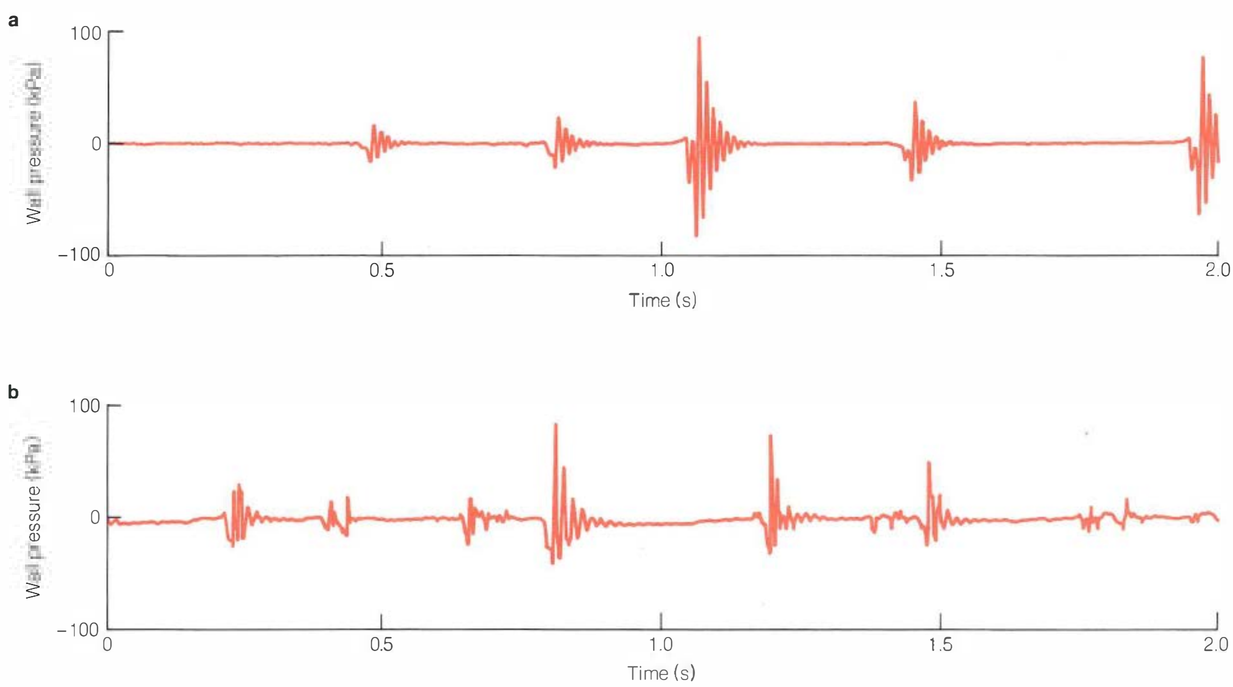
The difficult part of the analysis is to model the statistical nature of the triggering mechanism. There are two stochastic variables to consider—the frequency of the eddies hitting the interface and the amount of temperature drop at the interface caused by these cold eddies.

The large quantity of experimental data accumulated in the SRI study makes it possible to derive joint statistical distributions as functions of geometry and of thermal-hydraulic variables. Preliminary calculations have indicated that the statistical model successfully reproduces the main characteristics of the pressure loads measured at the wall (Figure 4). When the water temperature in the pool is sufficiently high and when the flow rate of steam is increased sufficiently or noncondensable gas (such as air) is mixed with the steam, it is possible to create a steam bubble at the vent exit that will not collapse completely. Instead, the interface oscillates regularly on either side of an equilibrium position. This oscillation, which creates a specific type of signal at the containment walls, is called condensation oscillation. Because of its regularity, this phenomenon may induce resonance in the containment walls and create significant structural loads, even though the peak pressure amplitudes are small.

The causes of condensation oscillation are not yet fully understood, but preliminary analyses have indicated that the regular oscillations might be caused by acoustic waves in the steam volume. To verify this hypothesis, a mechanical oscillator was inserted in the vent. The frequency of oscillation was continually varied. Preliminary observations indicated that the bubble oscillations were coupled to the oscillations in the vent for a discrete set of frequencies. Further analytic and experimental investigations are under way to confirm or disprove this effect.

As a result of this project, a general com-

**Figure 4** Comparison of calculated and measured wall pressures produced by condensation oscillation in a containment: **(a)** the statistical approach displays pressure disturbances with different amplitudes and different time intervals, and **(b)** a similar pattern is observed experimentally.




puter code was developed at Jaycor to model vapor-liquid interface motion with considerable detail and accuracy. The computer code SAMPAC is capable of following the trajectories of particles attached to the steam-water interface, thereby predicting at all times the shape of the steam bubble and the motion of the pool's free surface.

SRI is undertaking a complete mapping of the range of conditions under which condensation oscillation appears. Future development should bring more insight into condensation oscillation and provide a complete statistical model for chugging. *Project Manager: Jean-Pierre Sursock*

# R&D Status Report
# ELECTRICAL SYSTEMS DIVISION

John J. Dougherty, Director

## UNDERGROUND TRANSMISSION

### Magnetic refrigerator development

Low-cost, high-efficiency refrigeration is an important adjunct to any forced-cooled transmission line. It is an indispensable component of a cryogenic system, such as a superconducting transmission line. Ordinary gas expansion-compression refrigerators are limited to a relatively low efficiency (10–30% of Carnot). However, a magnetic refrigerator has the potential for much higher efficiency and lower capital cost and can be much more compact.

With this in mind, a research project was undertaken with the Los Alamos Scientific Laboratory (University of California) to develop a magnetic refrigerator (RP7867). The design goals for the first prototype are 1000 W of refrigeration from +20°C to −20°C, at 70% of Carnot efficiency. If successful, the implications are twofold. First, the refrigerator is of immediate value to conventional forced-cooled lines. Second, the applications of this technique at much lower temperatures need to be demonstrated for superconducting cables.

As part of this 18-month project, a magnetic refrigerator was built and will be tested early this year. Deviations from the theoretical design goals may occur in the first model. However, it will represent a significant achievement even if only 50% of Carnot efficiency is achieved. *Project Manager: Mario Rabinowitz*

### Backfill materials for underground cables

On hot days when load increases and the interface temperature between underground cable and soil rises, drying of the soil occurs, severely limiting heat transfer from cable to soil. Should this process continue, the circuit may overheat.

Phase 1 of a project completed in June 1977 promises a solution to this problem (RP7841). Extensive analyses were made of materials that could be added to soil to improve its thermal properties and stability. The most promising additive is wax, which allows a soil's thermal resistivity to be a function of the amount of additive used and not the amount of water present.

Thermal resistivity in semipermeable material, such as soil, is usually a function of the inherent grain structure, screenings (grain size), dry density (compaction), and content of water in the interstices. Figures 1 and 2 show how resistivity in a good thermal sand (Fire Valley) varies with water content and dry density, respectively. In Figure 1, polymer-treated sand, resistivity is still a function of moisture content. Figure 3, in which the Fire Valley sand has a 6% wax additive, shows a relatively flat curve even

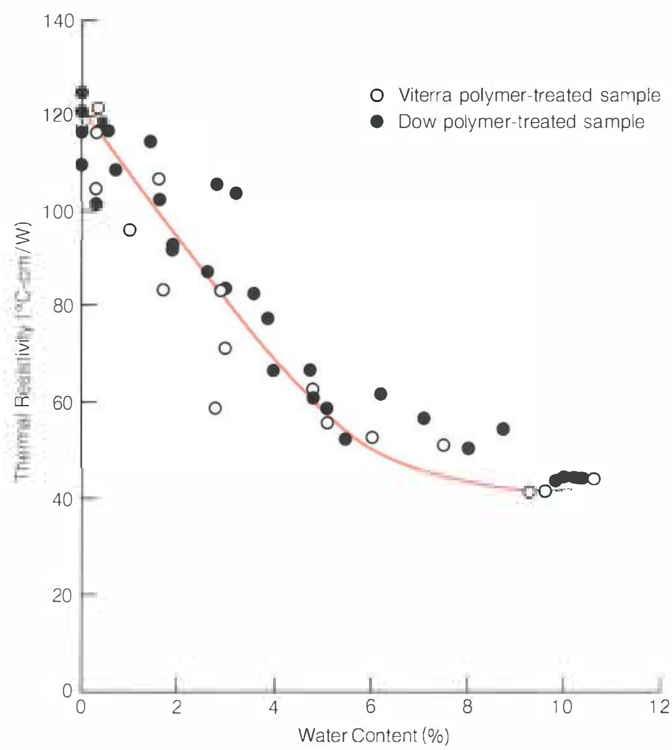
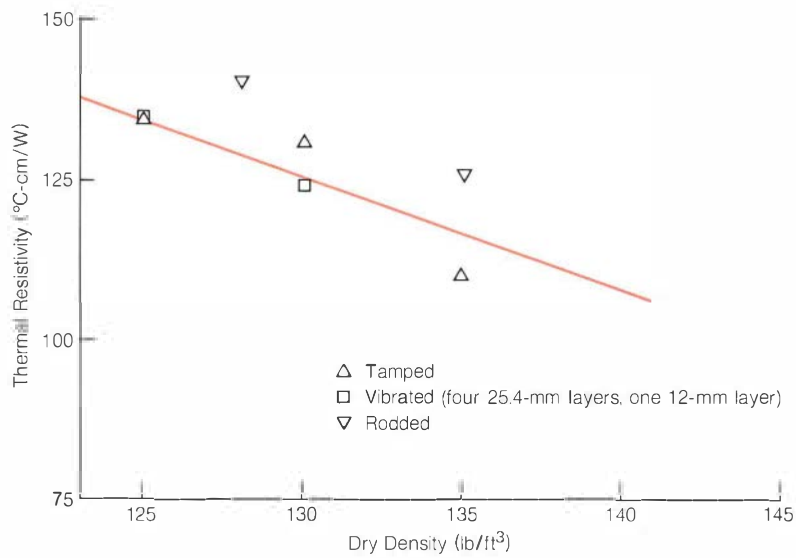



**Figure 1** Variation of the thermal resistivity of polymer-treated Fire Valley sand with percentage of water (measured by weight). Dry density of the sand is 1.9 Mg/m³ (120 lb/ft³).

Figure 2 Thermal resistivity plotted as a function of dry-sand density, with three different methods of compaction.



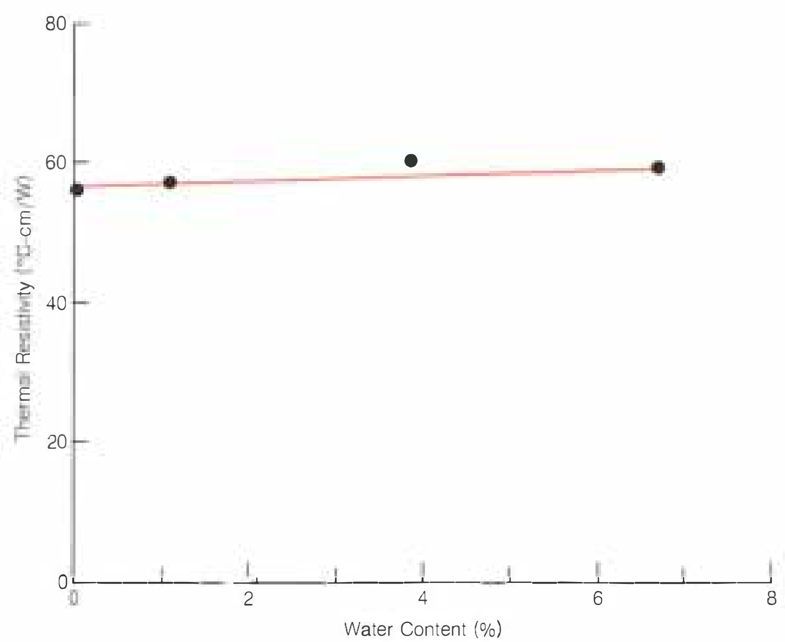




Figure 3 Effect of moisture on the thermal resistivity of Fire Valley sand that has been stabilized with 6% wax additive (by weight). This plot shows the virtual independence of resistivity with water when wax is added.

when moisture is varied. When wax is used, low-resistivity values persist even when complete drying occurs.

Phase 2 of this project at University of California at Berkeley, Richmond Field Station, will validate computer predictions of thermal profiles and moisture movement with data from the long-term proof-testing of wax. By field-testing the backfill, using standard trenches and buried heat pipes, the mechanical durability, long-term effectiveness, and performance of the composite (wax in different backfills and soils) can be ascertained. *Project Manager: Thomas Rodenbaugh*

## Screening program for porous polymers

The use of synthetic polymeric materials for laminar cable insulation is being considered for transmission cables at the 500-kV level and above. A 1½-year project was initiated in mid-1977 at the National Bureau of Standards (NBS) to develop a screening program and to focus on a testing methodology that would ensure selection of the best synthetic polymers (RP7864).

NBS completed a state-of-the-art survey on cable making and developed a tentative, three-phase screening approach for the use of those who wish to evaluate polymeric materials for cable applications. NBS will next identify test methods that will provide the information required for the evaluation.

As part of the test method, NBS is developing a unique means to determine the extent to which voids in the polymer are filled by cable oil. When the work is concluded, the test method and the three-phase screening program will be published. *Project Manager: Bruce Bernstein*

## Taped cables

The utility workhorse in underground transmission has been oil-impregnated, cellulose-paper-taped cable systems. Their long history of use has resulted in highly optimized systems. Relatively cheap dielectric materials (cellulose paper and dielectric-quality natural or synthetic oil) that are inherently resistant to degradation have produced a cable system without equal. However, there are no reliable, economic alternative systems in underground transmission at 230 kV and above.

The development of improved alternatives to cellulose-oil systems can take two paths. The first consists of research into promising systems with considerably different dielectric materials, such as cross-linked polyethylene or $SF_6$. The second consists of maintaining the system's basic construction features (i.e., a taped dielectric with a suitable impregnant) but with radically improved economics or ampacity by using better materials. This latter option, in fact, becomes necessary in most conventional self-cooled systems above 500 kV because of the high dielectric losses present in cellulose-oil dielectrics at these voltages. An economic, low-loss tape (film or paper) insulating system needs to be developed.

In two projects with this goal, General Cable Corp. developed a 500-kV synthetic-laminar-insulated cable (RP7810), and Phelps Dodge Cable and Wire Co. developed a 750-kV synthetic tape cable (RP7812). The magnitude of the problems to be solved justified a dual, albeit parallel, effort. Funding was provided by EPRI, DOE, and the contractors.

In both projects, all available, electrically suitable, synthetic materials were screened in search of a workable combination of tape and fluid impregnant. A laminate of cellulose paper on both sides of a polypropylene (PPP) film was chosen independently by both contractors as the best tape dielectric. Silicone oil was the impregnant used in RP7810, and a special grade of polybutene oil was used in RP7812. The combination of PPP tape and a particular impregnant involves many trade-offs in the solution of specific operating problems. Unfortunately, because of recent cost increases, the silicone oil system is expensive compared with conventional oil-cellulose-paper systems. Hence, testing of the 500-kV, silicone-oil-insulated cable will not be pursued.

The 750-kV PPP-polybutene oil system, however, will be evaluated at the Waltz Mill Underground Cable Test Facility. An economic, low-loss underground transmission cable system has been developed and will be a useful alternative where congestion, right-of-way, or other considerations prevent overhead construction. On successful completion of accelerated life testing, this option should be technically and economically attractive. *Project Manager: John Shimshock*

### Dc transmission

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

The electrical, mechanical, thermal, and hydraulic parameters of these very large diameter cables impose constraints on their manufacture, shipment, installation, and operation, and hence on the highest attainable power and voltage ratings. BICC is conducting experimental and analytic work to characterize these constraints. *Project Manager: Felipe Garcia*

## POWER SYSTEM PLANNING AND OPERATIONS

### Defining transmission component outages

There is a growing interest in the application of probability methods for a quantitative evaluation of transmission system reliability. A major difficulty facing the industry is the lack of outage statistics for various transmission system components. Several utilities and pools have data collection systems in operation or under development. However, uniform definitions and reporting procedures are needed so that the data can be compared and pooled to provide increased confidence in the results.

The objective of a two-year project with General Electric Co. is the development of consistent definitions and procedures for collection of outage data on transmission system components (RP1283). The results of this project will enable utilities to achieve consistent data collection, from which they can establish a broad data base.

The primary application of this work is to develop outage statistics for reliability analyses that can be used in system planning and operations. The data may also have applications for component design or performance evaluation.

Outage data of interest cover all bulk power system components from the generator terminals to the distribution substation, including transmission lines, transformers, circuit breakers, and so on.

In this project no planning or operating standards will be developed. No methods will be suggested that would rightly be in the domain of individual utilities and pools.

The liaison group that will review the project milestone reports includes representatives from NERC and its regions and from EEI, APPA, NRECA, and IEEE. It is hoped that such broad review of the project results will make them acceptable to a wide range of utilities and pools.

Of the four interrelated phases of this project, the first phase is nearly complete. It consisted of interviews with utilities and pools that are actively evaluating their own data collection procedures, studies of data collection schemes in Europe, and a survey of the technical literature.

A comprehensive questionnaire was developed to guide a series of discussions with the industry. The topics include current and future applications of outage data, existing and planned data systems, outage-reporting procedures, outage classifications, population and exposure data, and data processing and analysis. So far, discussions have been held with Commonwealth Edison Co., Pennsylvania–New Jersey–Maryland Pool, Northeast Power Coordinating Council, Florida utilities, the Mid-continent Area Power Pool, Bonneville Power Administration, and Pacific Gas and Electric Co.

During Phase 2, the raw data requirements will be determined for reliability calculations in bulk transmission systems. An important part of this phase will be to investigate present methods of collecting data on multiple outages and other events that involve a combination of component outages, including failures of relay systems. This phase should result in a list of component categories and failure modes for which outage data should be collected, together with a ranked list of applications and data requirements.

In Phase 3, a flexible method for reporting outages and formats for collecting data will be designed. Special attention will be given to the fact that data on a given outage must be collected from several sources, as well as over a period of time. A second basic concern will be to minimize the utility's burden of reporting without sacrificing the necessary detail. During Phase 4 an optimal data base structure and data management system will be devised. *Project Manager: M. P. Bhavaraju*

### Reliability indexes for power systems

The evolution of planning criteria in each of the three power system segments (generation, transmission, and distribution) has resulted in reliability indexes that are appropriate to each sector. The underlying objective of reliability criteria is to provide a basis for balancing cost and reliability. However, the primary application of reliability indexes has been as a consistent basis for planning.

In recent years, the increased cost of new facilities, the scarcity and cost of capital, and concerns with environmental and other social issues have led to greater interest in the development of customer-oriented reliability indexes. One advantage of such indexes would be their ability to serve as absolute (rather than relative) measures of reliability.

The objective of a two-year project undertaken by General Electric Co. (RP1353) is to evaluate the reliability indexes that are in use or have been proposed and to define and develop more meaningful indexes. In the evaluation and development of indexes, primary consideration will be given to those that

- Respond to the basic planning parameters and are suitable for consistent planning of generation, transmission, distribution, and the overall power system
- Reflect service quality from the customer viewpoint
- Are suitable for quantifying reliability worth
- Are helpful in communicating with non-technical people
- Are feasible for computation with existing and future methods

The work done so far includes an evaluation of existing reliability indexes. In the generation area, a number of different indexes used by the industry were identified. These indexes were evaluated from the standpoint of computation, assumptions, sensitivity, and information gained.

Transmission reliability, on the other hand, could not be characterized by any specific indexes that could be used as planning criteria. The analysis in this case identified the various factors considered by different utilities and pools and classified them as failure measures, types of events examined, various reliability calculations performed, and the methods used to solve the problems. The generic differences between generation and transmission reliability are being examined further.

A listing of the specific planning questions that need to be answered is being prepared. This will serve as a yardstick against which the adequacy of existing and proposed indexes can be measured.

The results of this work will form one or more hierarchical systems that combine existing and new reliability indexes. A unified mathematical structure for the proposed indexes and the analytic relationships that would exist between the indexes will be developed. The techniques used in calculating the indexes (including data, computer algorithms, and the necessary assumptions) will be evaluated. The indexes will be applied to a synthetic utility system to assess their ability to meet the objectives of this project. *Project Manager: M. P. Bhavaraju*

## SUBSTATIONS

### HVDC electronic current transducer

A digital electronic current transducer (ECT) for high-voltage direct current (HVDC) applications has been built, tested, and installed in an HVDC terminal for long-term testing. The HVDC–ECT, which meets the applicable accuracy requirements for metering purposes, was developed by General Electric Co. under RP668-1 (*EPRI Journal*, December 1977, pp. 51–52). The 400-kV, 2000-A test unit that was installed at the Sylmar Converter Station by the Los Angeles Department of Water and Power is shown in Figure 4.

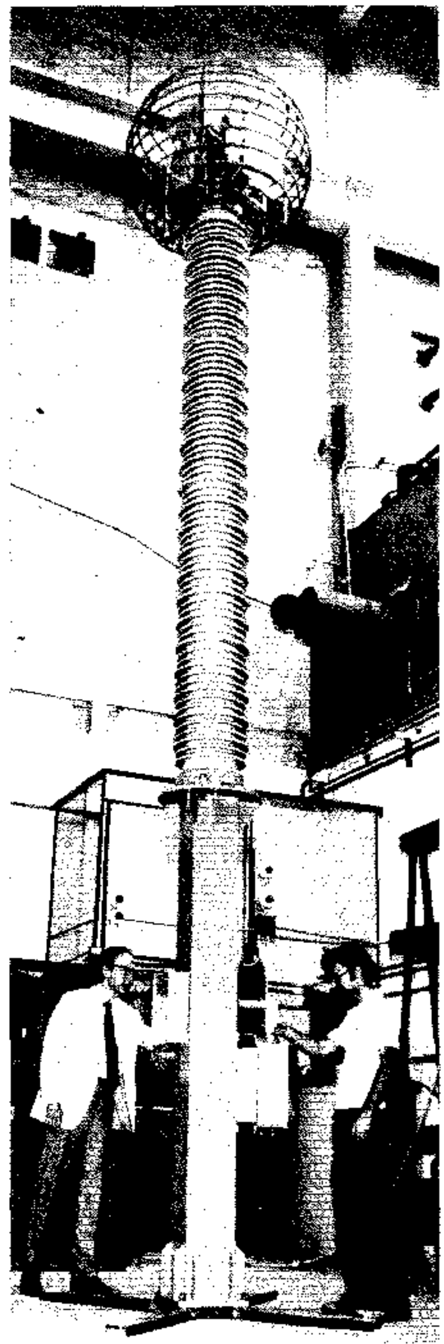
The top of the unit contains a 100-$\mu\Omega$ shunt for current sensing, a 14-bit analog-to-digital converter, and an encoder for a fiber-optic data link. This link is used for data transmission to ground level. The fiber-optic receiver and decoder is located in the control room, which may be as far away as 300 m. The porcelain column, shown in Figure 4, provides the necessary support for the unit and also houses the optical fibers and a 30-kHz, 10-stage cascade transformer link for power supply from ground level to the electronics in the energized head of the unit.

The development of the electronic system for the current measurement was, of course, the major task in the project. Some other R&D areas of interest were the development of a suitable shunt, the fiber-optic system integration, and the power supply system design.

It may seem strange that a suitable shunt could not readily be found on the commercial market. However, the accuracy requirements of the system could not be met with available shunt designs within the specified temperature range ($-40$ to $+50°C$) and an operating range from 0 to 2000-A with a 4000-A overload rating. After investigating many shunt materials, it was decided that a design based on Cupron material best met the requirements.

A Siecor fiber-optic system with two types of cable was selected for data transmission

Figure 4 A 400-kV/2000-A digital electronic current transducer (ECT) of metering accuracy was developed for high-voltage dc (HVDC) applications and installed for long-term testing at the Sylmar Converter Station by the Los Angeles Department of Water and Power. The top of the unit contains a current shunt and electronic equipment for conversion of the current to an optical signal. This signal is transmitted via hair-thin, optical waveguides brought from the control room of the terminal, through the porcelain column to the top of the unit. The porcelain column houses a power supply system that feeds power to the electronic equipment in the energized head of the unit. The optical signal is reconverted to an electric signal in the control room, which can be as far as 300 m from the ECT.



from the energized head of the ECT to the control room. A new type of cable with a void-free, solid buffer was used between the energized head of the ECT and ground. This solid buffer is desirable to avoid corona problems and also to get a pressure-tight seal where the cable goes through an end-plate of the porcelain column. At ground level, a conventional Siecor low-loss, optical communication cable takes over for the remaining distance to the control room.

Various methods were investigated for the supply of power to the electronics in the energized head of the ECT. It was determined that in most HVDC applications, a power supply from ground level would be required. This contrasts with ECTs for ac applications, where the power supply in many cases can be taken from the ac line itself (*EPRI Journal,* May 1978, pp. 51–52). The power supply link for this HVDC–ECT must go through the dielectric system, providing isolation for the energized components from ground. This penetration must be made in such a manner that the dielectric strength of the insulation system is not diminished. Hence, the selected high-frequency, cascade transformer link selected for this test unit has built-in potential grading circuits. These may, in fact, make the dielectric system electrically stronger than the ungraded column by providing improved voltage distribution in the support column.

The HVDC–ECT has passed all factory tests, including high-voltage and high-power tests. As mentioned above, the unit has been installed in one pole of the ±400-kV, 1800-A southern terminal of the Pacific HVDC Intertie for at least one year of testing to verify the long-term accuracy of the unit. *Project Manager: Stig Nilsson*

### Static VAR generator

Mounting interest in static control of volts-amperes reactive (VARs) was evidenced by attendance at a recent seminar on the subject sponsored by EPRI and Minnesota Power & Light (MP&L) Co. Over 140 representatives from 30 utilities and 9 manufacturers (some from other countries) were among those present. A featured event was a visit to MP&L's Shannon 115/230-kV substation, where an EPRI-funded static VAR generator, developed and manufactured by Westinghouse Electric Corp., has been in operation since August 1978 (RP750). In addition to its normal operation and its support of voltage during disturbances of both loads and generation, the generator has been undergoing a series of systematic trials to evaluate its various facets.

Westinghouse developed, under EPRI contract, light-fired thyristors that can replace electrically fired thyristors and can allow simplified firing circuitry. A switch module of light-fired thyristors being designed and fabricated by Westinghouse will replace one phase of the electrically fired switch after one year of acceptance testing of the existing installation. Tests will then take place to evaluate the light-fired module. *Project Manager: Gilbert Addis*

René Malès, Director

## WATER RESOURCE CONSTRAINTS ON ENERGY PRODUCTION

*Developing energy resources and generating electric power require substantial amounts of water. The water is needed in cooling operations for energy resource development and thermoelectric power production and in the processing of synthetic fuels. Yet U.S. energy-economy models do not explicitly take account of the availability of water for energy resource development and energy production. Stanford University is determining how to integrate water resource constraints into energy models (RP1304-1).*

Estimates show impressively large quantities of surface and groundwater in the conterminous 48 states. The average aggregated streamflow is about $2.3 \times 10^{12}$ m³/yr ($1.9 \times 10^9$ acre-ft/yr), and groundwater within 750 m (2500 ft) of ground surface amounts to $120 \times 10^{12}$ m³/yr ($100 \times 10^9$ acre-ft/yr). However, the distribution of water resources does not parallel that of energy reserves, and in areas where water is relatively scarce or where it is already used by or reserved for other sectors of the economy, it may influence appreciably the rate at which energy resources could be developed. Hence, the effects of water scarcity should be reflected in models for energy R&D planning. Also, the availability of water supplies that are adequate in quantity and in quality ranks as an important criterion for the siting of thermal-electric power plants, together with the proximity of fuel supply and load centers.

To highlight some of the critical issues that may arise in water-energy interactions, a regional water-energy-economy model needs to be developed. One of the models studied in this project is RESOM (Regional Energy Systems Optimization Model), developed recently at the Brookhaven National Laboratory. It has the capability to emphasize regional differences and also to integrate the regions within the entire United States. The model has two major components: a multiregional, interindustry, input-output (I–O) submodel and a multiregional, linear programming (LP) submodel that represents energy operations in detail. Equations representing the water sector were integrated in the I–O submodel, and constraint equations showing regional availabilities of water resources were added to the LP model. The structure of the model is given in Figure 1. The figure shows a possible method for solving the model, which is to converge iteratively to a solution of the I–O submodel, thus reflecting a national and regional water-energy-economy system.

The regional input parameters to the I–O submodel are:

- Gross regional product by purchasing sector and industry
- Interindustry technical and trade coefficients, except those recalculated after the

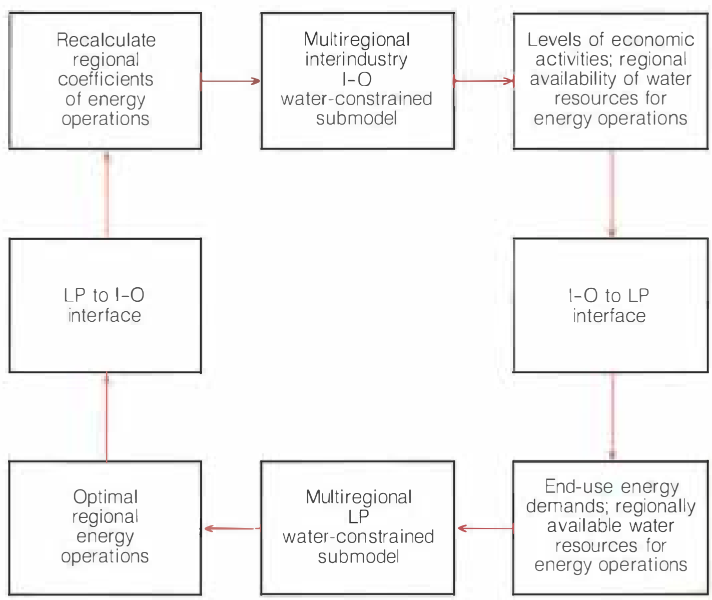



Figure 1 Structure of a water-constrained energy-economy model, showing an iterative solution sequence.

solution of the LP submodel

▫ Regional availability of water resources, municipal uses of water (based on population estimates), and water-use coefficients for food production (irrigation), manufacturing, and energy-related activities

The regional input parameters to the LP submodel are:

▫ Load and plant factors of energy technologies

▫ Efficiencies of energy conversion and transportation

▫ Environmental limitations on discharge of residuals into the atmosphere and into water

▫ Unit costs of energy production

▫ Limitations on energy capacity, trade, extraction, and use

▫ Water-use coefficients in energy operations

The model is a single-period static model; that is, when its input parameters are adjusted, it can be used to evaluate a given policy at any point along the time axis.

Only the LP submodel of RESOM has been developed; the regional I–O submodel is yet to be completed. Nevertheless, the LP submodel alone was used in this project to determine the feasibility of integrating water resource constraints into existing energy models, yielding a matrix of over 1700 rows and some 3000 columns. Among the computer runs made, one used 1975 data and, as expected, water was not found to be a constraining element. Other runs used a scenario for the year 2000, and preliminary results indicate that water resource constraints may appreciably influence the rate at which energy resources could be developed. To further investigate the key issues of water resource constraints, continued research will develop an improved regional scheme. This will emphasize the problems of water-energy interactions and identify areas where water scarcity may significantly inhibit the rate at which energy resources may be developed. *Project Manager: Richard Richels*

## ECOLOGICAL EFFECTS OF ACID DEPOSITION

*To identify the role that atmospheric deposition plays in lake acidification, chemical budgets of three watersheds with lakes of different acidity are being analyzed. The first year of field data collection has been completed, and a computer simulation model of the watershed systems is being implemented.*

An extensive field study in the Adirondack Mountains of New York (Figure 2) is being undertaken to determine the role that acid deposition plays in the reported increasing acidity of lakes in the region (*EPRI Journal*, June/July 1977, p. 36). Increasing lake acidity has also been reported in areas of Canada, Scotland, Norway, and Sweden.

The results of this research in the Adirondacks (RP1109 and RP1155) should help resolve what was identified as a major subject of uncertainty at an international workshop held last September on the ecological effects of acid deposition (SOA 77-403). The workshop was sponsored by EPRI and organized by England's Central Electricity Research Laboratories. Participants included scientists who have been studying acid deposition effects in the United States, Great Britain, Canada, Norway, Sweden, Germany, and Poland. The objectives of the workshop were to evaluate the results of previous studies, draw conclusions, and identify questions to be resolved. One major need identified was to quantify how atmospheric deposition influences the acidity of soils and surface waters compared with other ecosystem sources and sinks of acids (hydrogen ions). Major potential sources of acidity in the soil include respiration of roots and microorganisms, uptake of elements by plants, nitrification in arable soils, oxidation of sulfides, and decomposition of organic residues. Sinks can result from weathering of minerals in soil and rock, cation exchange, and leaching by surface waters. The acids removed by surface waters contribute to the acidification of streams, rivers, and lakes.

The study site for the Adirondack project consists of three forested watersheds (Table 1 and Figure 3). Each watershed contains a lake of different acidity. If it is assumed that each watershed receives identical atmospheric inputs, then properties of the watersheds themselves must account for the different acidities of the lakes. The assumption of identical atmospheric inputs is being checked experimentally by daily collection and chemical analysis of precipitation in each watershed and weekly analyses of snow cores during the winter (Figure 4). The study is designed to identify the different watershed properties and explain how they determine the acidities of the lakes. To do this, the flow of water through the watershed must be traced (Figure 5). It is important to determine how the composition of the water is affected by interaction with different

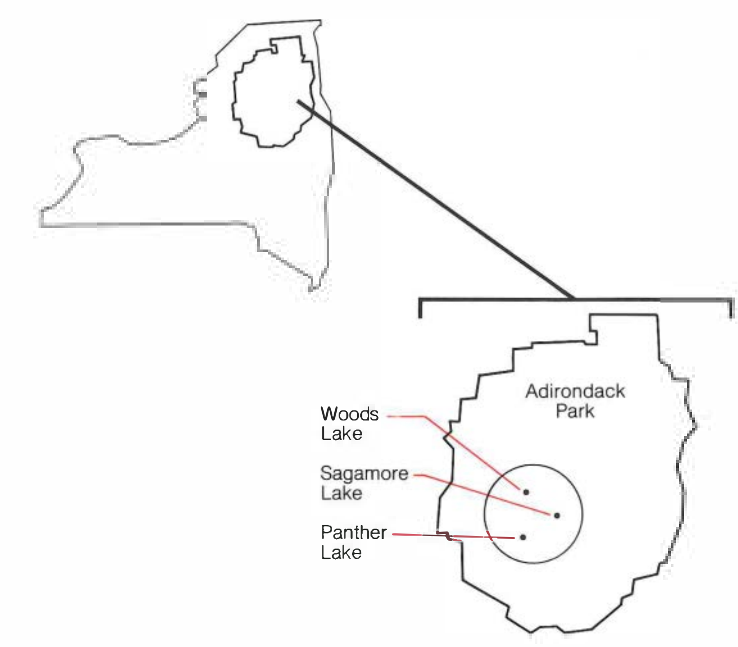



Figure 2 The Adirondack area (New York), where the lake acidification study is being conducted.

**Table 1**
**PHYSICAL CHARACTERISTICS OF ADIRONDACK WATERSHEDS**

| | Watershed | | | | Lake | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Area ($km^2$) | Relief (m) | Forest Cover (%) | Bedrock Outcrop* (%) | Altitude (m) | Area ($km^2$) | Volume ($10^5 m^3$) | Mean Depth (m) | Maximum Depth (m) | Alkalinity (meq/l) | pH |
| Panther Lake | 1.24 | 174 | 100 | 40 | 557.2 | 0.18 | 7.09 | 4.0 | 7.0 | 100 | 7.0 |
| Sagamore Lake | 49.65 | 561 | 97 | 40 | 580.3 | 0.72 | 75.40 | 10.4 | 23.0 | 10 | 5.5 |
| Woods Lake | 2.07 | 122 | 100 | 80 | 606.6 | 0.23 | 8.13 | 3.4 | 12.0 | −20 | 4.6 |

*Mean soil depths less than 6 cm.

Figure 3 Sagamore Lake watershed, one of three lake watersheds where chemical budgets are being analyzed to identify the contribution of atmospheric deposition to lake acidity. In the lower right corner is Aluminum Pond, which is surrounded by an extensive bog.

Figure 4 Atmospheric deposition and meteorological monitoring equipment in the Woods Lake watershed.

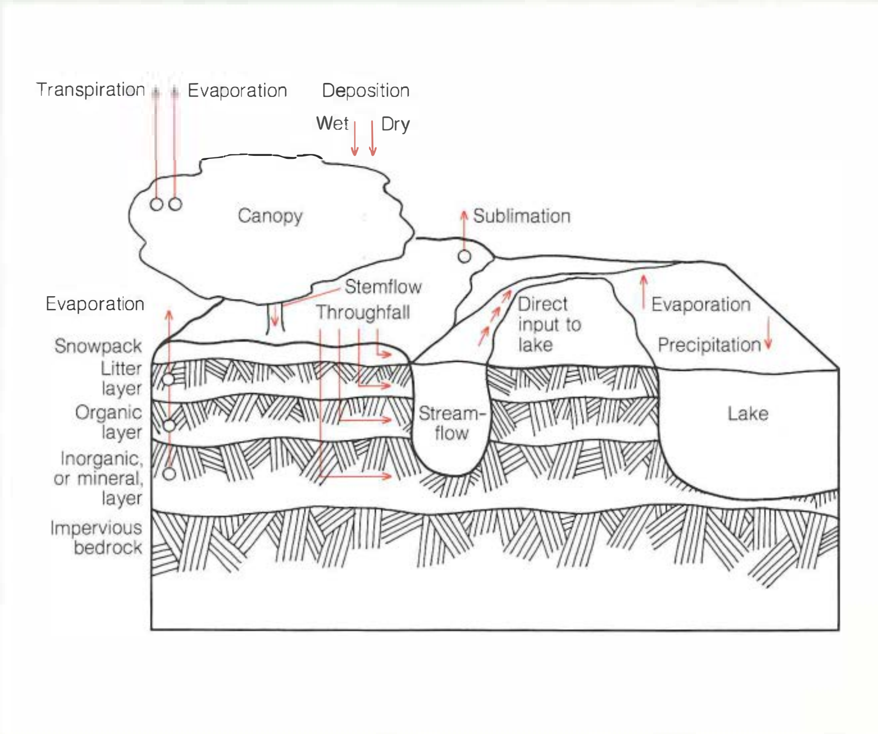
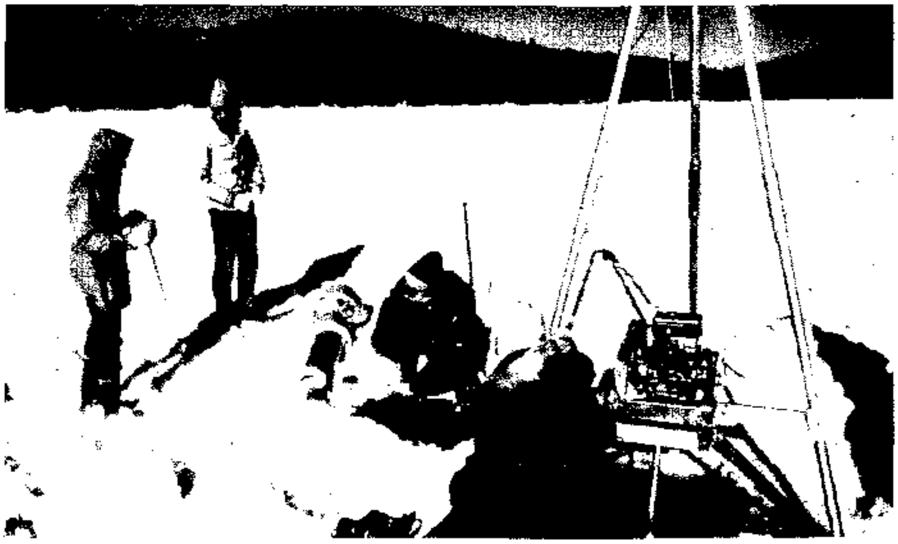



Figure 5 Pathways for water movement through a forested watershed.

Figure 6 Drilling for lake sediment samples occurs in winter when the ice cover permits the drill to be positioned in the middle of the lake.



watershed components, for example, vegetation, litter, organic layer of soil, inorganic layer of soil, bedrock, and lake sediment. These interactions change with the seasons. During winter, for instance, the behavior of chemicals in the snowpack becomes an important consideration.

This study is complex and involves such diverse disciplines as micrometeorology, plant-nutrient relations, plant-water relations, soil physics, soil chemistry, geology, hydrology, limnology, and mathematical modeling. This complexity demands the close cooperation of many scientists of diverse backgrounds, who are affiliated with Cornell University; Rensselaer Polytechnic Institute; United States Geological Survey; Tetra Tech, Inc.; Woods Hole Oceanographic Institute; U.S. Department of Energy, Environmental Measurements Laboratory; University of Virginia; Brookhaven National Laboratory; Harwell Laboratory (U.K. Atomic Energy Research Establishment); State University of New York at Brockport; and State University of New York at Oswego. Data collected in research projects sponsored by New York State Energy Research & Development Authority and the U.S. Office of Water Research and Technology at the Adirondack study site complement the EPRI project.

The study is still in its initial stages—only the first year of data collection has been completed. A mathematical computer model of water movement and reactions through the system will be used to analyze collected data. Sensitivity analyses will be performed to suggest which ecological processes are most important in determining lake acidity.

Another objective of the study is to determine the acidification history of the three lakes. This is being attempted by taking sediment profiles (Figure 6), identifying plankton remains in the strata of the profiles, correlating the identified plankton with pH tolerances, and dating the strata by radioisotope methods.

During a detailed technical review of the study last October, EPRI consultants and electric utility scientists identified several aspects that needed further emphasis. These include measurement of evapotranspiration, estimation of dry deposition, measurement of the quality and quantity of groundwater inputs, and coordination between EPRI and other sponsored research. *Project Managers: Robert Goldstein and Charles Hakkarinen*

## FORECASTING RESIDENTIAL ELECTRICITY CONSUMPTION

*A new generation of residential load and energy consumption forecasting projects has recently been placed under contract. To date the mainstay of the Demand and Conservation Program's forecasting activities has been aggregate state and national models, such as those employed in* Demand 77 *(EA-621-SR). Although these models will continue to play a central role in demand and conservation forecasting, the new generation of models will improve the quality of these forecasts and expand their scope to include household-level behavior. Two separate but interrelated lines of research, aggregation and microsimulation, will be used in the optimization of existing demand and conservation forecasting models.*

### Aggregation

The first line of research examines the aggregation problem. Aggregates are used for forecasting because it is difficult to represent such variables as future income and family size for individual families. What formal mathematical procedures should one follow to obtain aggregate, or state, models that correctly predict the collective behavior of thousands of households? Because of data limitations, aggregate models are usually based on some average value of household variables, such as average household income in a state. By their nature these averages will generally lose information on how particular subsets of households behave. Averages do not fully represent the distribution of individual household characteristics. Average household income, for example, does not indicate the number of very high or very low income households in the sample. Yet, in some cases, the distribution of income may have important implications for energy consumption. The aggregation problem involves the question of how to construct and use averages or aggregate measures to best represent the behavior of individual households. Dale W. Jorgenson Associates is studying the aggregation problem in an effort to develop a national model whose forecasts are consistent with the behavior of individual households (RP1428). Jorgenson will develop models at the household level and then estimate national models that are consistent with the household-level information.

National Economic Research Associates, Inc. (NERA), is also examining the aggregation problem (RP1361). EPRI will incorporate the results of this project and those of RP1428 into a number of advanced econometric models now being developed. These models will be used by EPRI in energy consumption forecasts.

The Institute for Social Research at the University of Michigan and the University of Arizona are conducting a third project that touches on the aggregation topic (RP1363). They are developing models of household energy consumption and load characteristics, using several data sets from demonstration projects on time-of-day pricing. This project will also provide useful household-level information for the Jorgenson and NERA studies.

## Microsimulation

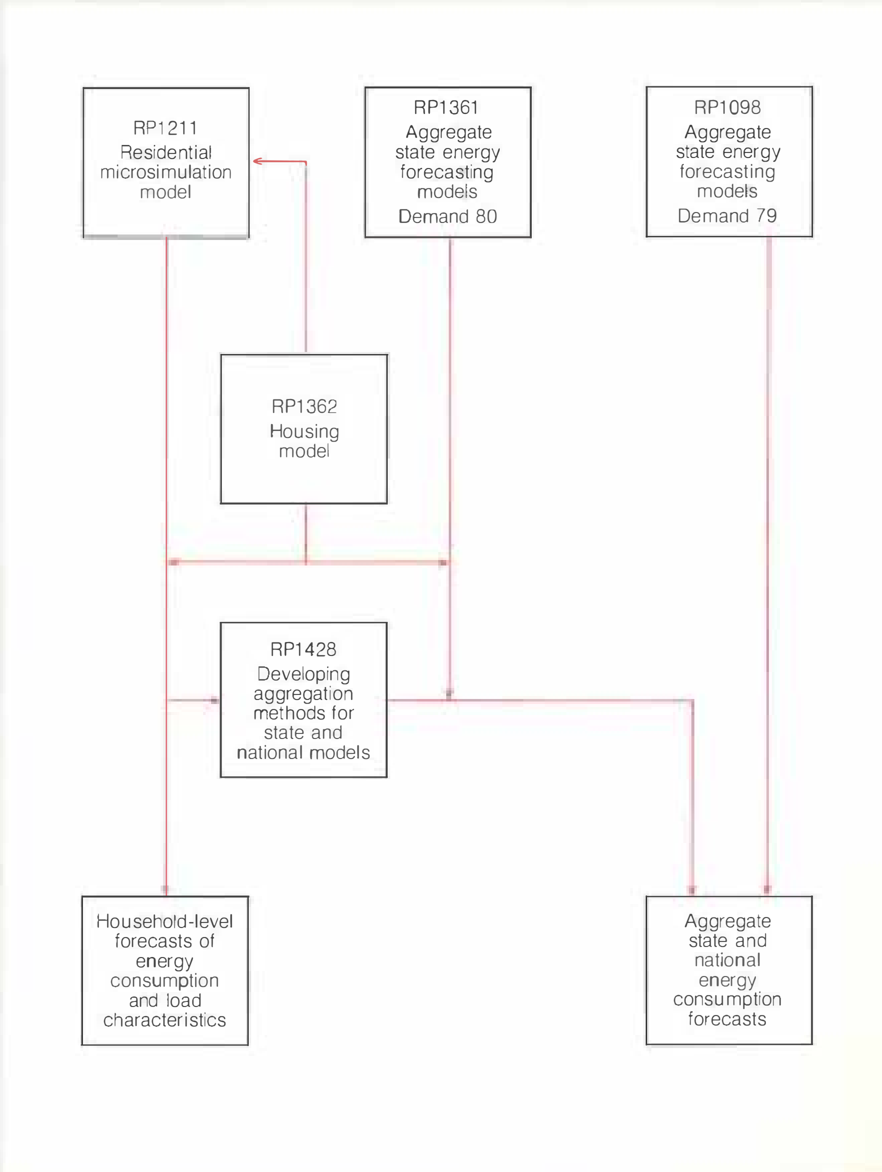
The second line of research in the new generation of forecasting projects is microsimulation modeling. Microsimulation models use a representative sample of individual households. The behavior of each household is individually modeled, and aggregate behavior is determined through aggregation over the sample. Microsimulation models include data on the entire distribution of household characteristics (including energy-using equipment) and dwelling characteristics, rather than being restricted to the average behavior of all households, as is common with conventional econometric models.

Microsimulation is a useful tool for analyzing new technologies and dwelling characteristics for which there are limited data because the simulation nature of the model allows one to incorporate engineering and architectural information about new technologies along with historical data on existing technologies. Thus, these models can aid in assessing the implications of energy conservation policies, such as income tax incentives for solar equipment and insulation, federal building standards, appliance efficiency standards, and load management and time-of-day pricing.

To deal with those household-level forecasting issues, the Demand and Conservation Program initiated a study with Cambridge Systematics, Inc., to develop a microsimulation model of residential energy consumption and load characteristics (RP1211). This model will ultimately produce regional and state forecasts based on large numbers of individual households. Approximately 3000 households will be used to characterize a particular region or state, with several thousand possible combinations of socioeconomic and dwelling characteristics for any particular household. The model would, for example, include 30% of households described as detached single-family dwellings with electric space heating and two working adults, if these were the proportions observed in the state. This level of detail facilitates the wide variety of policy analysis described above.

The microsimulation model requires extensive detail on housing construction to the year 2000. Existing aggregate models of energy consumption could also be improved by accurate projections of housing construction. This need will be met by the first phase of a project being conducted by Data Resources, Inc. (RP1362). In this study, a number of housing data bases will be assembled into a user-oriented data management system. Subsequent studies will develop models based on these data.

Figure 7 Interrelationships between existing and future residential energy models. At top right is the state model (RP1098), which is being used to produce 1979 in-house EPRI national demand forecasts. This project is conducted jointly by Data Resources, Inc., and Lester Taylor (University of Arizona). At top left is the microsimulation model (RP1211), which will interact closely with the housing model to be developed from the data in RP1362. The combined housing and microsimulation outputs will be used in aggregation research for state and national models (RP1428). These models will provide input for RP1361, which is designed to produce improved aggregate state and national forecasts. This research will then provide models for EPRI's future demand and conservation in-house forecasts.




The combined capabilities of these household-forecasting models, aggregation methods, and state models will provide EPRI with a dramatically improved basis for assessing energy conservation developments (Figure 7). The resultant forecasts and models will be used for EPRI's R&D planning and will provide models for use by individual utilities.

The microsimulation model will be particularly applicable to individual utility service areas for assessing the load and energy-using characteristics of new and existing technologies. This work will also provide an improved basis of understanding for public policy discussions of residential energy consumption and load characteristics. *Project Manager: James Boyd*

# New Contracts

| Number | Title | Duration | Funding ($000) | Contractor/ EPRI Project Manager |
|---|---|---|---|---|
| **Fossil Fuel and Advanced Systems Division** | | | | |
| RP128-5 | Development of Sodium-Sulfur Battery for Utility Application | 6 months | 1574.5 | General Electric Co. *J. Birk* |
| RP983-3 | Continuous Real-Time Assay of Coal | 5 months | 59.6 | Science Applications, Inc. *O. Tassicker* |
| RP991-8 | Penetration Analysis of Fossil Fuel and Advanced Power Generation Systems | 14 months | 8.3 | International Systems Consultants *O. Gildersleeve* |
| RP1180-3 | Economics of Four Flue Gas Desulfurization Systems | 1 year | 100.0 | Stearns-Roger, Inc. *S. Dalton* |
| RP1191-4 | Modular Solar System 300 Demonstration Home Monitoring | 2 years | 37.9 | Cambridge Electric Light Co. *G. Purcell* |
| RP1201-7 | Profile of Room Temperature and Energy Use for Radiant Heating Panels | 9 months | 8.6 | Kansas State University *Q. Looney* |
| RP1265-2 | Preliminary Approach to Root-Cause Analysis for Power Plants | 5 months | 29.9 | Science Applications, Inc. *J. Parkes* |
| RP1266-9 | Review of Acoustic Emission for Fossil Power Plants | 1 year | 59.9 | Science Applications, Inc. *J. Parkes* |
| RP1458-1 | Test Requirements for Aqueous Carbonate Process Demonstration | 4 months | 81.5 | Rockwell International Corp. *R. Rhudy* |
| **Nuclear Power Division** | | | | |
| RP620-28 | Study of Application of Electromagnetic Pump to 1000-MW (e) Pool-Type LMFBR | 5 months | 45.3 | General Electric Co. *J. Duffy* |
| RP707-3 | Characteristics of Fission Neutrons in Moderating Media | 15 months | 43.3 | Columbia University *O. Ozer* |
| RP710-3 | Development of Analytic Simulator for Fuel Management Analysis | 6 months | 33.9 | Nuclear Associates International, Inc. *B. Zolotar* |
| RP894-5 | Assessment of Value Problems Contributing to Nuclear Plant Unavailability | 3 months | 24.9 | Nuclear Services Corp. *T. Libs* |
| RP1172-3 | Optical Technique for Tube Diametrical Measurement | 6 months | 29.0 | Sigma Research, Inc. *G. Dau* |
| RP1323-1 | Statistical Methods for Establishing Safety System Margins | 2 years | 200.0 | Combustion Engineering, Inc. *A. Long* |
| RP1325-1 | Corrosion Fatigue Characterization of Reactor Pressure Vessel Steels | 3 years | 1275.0 | Babcock & Wilcox Co. *R. Jones* |
| RP1330-4 | Radwaste Evaporator Retreatment by Ultrafiltration | 13 months | 0.0 | Rochester Gas and Electric Corp. *A. Miller* |
| RP1335-2 | Scoping Capability for Fuel Management Applications in Pressurized Water Reactors | 14 months | 63.8 | Nuclear Associates International, Inc. *W. Eich* |
| RP1397-1 | Measurement of Sensitivity Depletion in Rhodium Self-Powered Neutron Detector | 16 months | 89.9 | Babcock & Wilcox Co. *G. Shugars* |
| RP1407-1 | Interaction Between Condensation and Shock Waves in Transonic Steam Flow | 2 years | 325.8 | Westinghouse Electric Corp. *J. Parkes* |
| **Electrical Systems Division** | | | | |
| RP7874-1 | Fault Location System for Transmission Cable | 22 months | 247.5 | Hughes Research Laboratories *T. Rodenbaugh* |
| **Energy Analysis and Environmental Division** | | | | |
| RP1220-4 | Cost Uncertainty in Mathematical Programming Models | 1 year | 50.0 | A. L. Fletcher & Associates *A. Halter* |
| RP1224-5 | Effects of Atmospheric Deposition of Coal Combustion Particulates on Terrestrial Ecosystems | 2 years | 249.9 | Battelle Memorial Institute *R. Kawaratani* |

# New Technical Reports

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

Inquiries on technical content may be directed to the EPRI project manager named at the end of each summary: P.O. Box 10412, Palo Alto, California 94303; (415) 855-2000.

**Requests for copies of specific reports should be directed to Research Reports Center, P.O. Box 10090, Palo Alto, California 94303; (415) 961-9043.** There is no charge for reports requested by EPRI member utilities, government agencies (federal, state, local), or foreign organizations with which EPRI has an agreement for exchange of information. Others pay a small charge. Research Reports Center will send a catalog and price list on request.

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Microfiche copies are available from National Technical Information Service, P.O. Box 1553, Springfield, Virginia 22151.

## ELECTRICAL SYSTEMS

### Near-Term Computer Capabilities and Their Impact on Power Flow and Stability Simulation Programs

EL-946 Final Report (TPS-77-749)

This survey by General Electric Co. of the entire class of vector processors available now or in the near future attempted to raise the reported low efficiency of sparsity-coded programs and to show how the most time-consuming parts of a simulation can be adapted to such machines. It was found that the efficiency of these processors is far less when they are used for problems for which they were not designed. However, small array processors (a type of vector processor) with sufficient floating-point word length promise an order of magnitude speed increase on these problems for a very reasonable price. Those portions of simulation programs requiring significant execution time but concerned with sparse equation solution can be vectorized for any of these machines. *EPRI Project Manager: John Lamont*

### Evaluation of Multiprocessor Algorithms for Transient Stability Problems

EL-947 Final Report (TPS-77-718)

This report by Northwestern University examines the possibility of using a dedicated multiprocessor network to do the step-by-step computations for the digital simulation of the dynamic response of a large power system. The solution method used in this study was based on the Bonneville Power Administration Transient Stability Program. Although over 97% of the computations for a typical 1723-bus, 398-machine stability study could be done in parallel, 30% of the computation time was spent solving the network equations. As the number of processors in parallel was increased for this part of the solution, a saturation effect was observed. *EPRI Project Manager: John Lamont*

## ENERGY ANALYSIS AND ENVIRONMENT

### Uranium Solution Mining Cost Model

EA-731 Final Report (RP803-2)

NUS Corp. and Mountain States Research and Development prepared a process-oriented computer model for estimating requirements and costs associated with a commercial, in situ, borehole uranium mining project.

The model was designed to provide a methodology for estimating the production cost per pound of $U_3O_8$ from a typical domestic sandstone uranium deposit and can accommodate a wide range of input parameters dictated by the user.

The programming methodology also includes a detailed hand computation procedure and an optional graphic analysis procedure. *EPRI Project Manager: Richard Urbanek*

### Polycyclic Organic Materials and the Electric Power Industry

EA-787-SY Summary Report (WS-76-67)

This project was undertaken by Battelle, Columbus Laboratories to verify the efficiency and analytic performance of the solid sorbent sampler, developed to collect polycyclic organic materials (POMs) from gaseous power plant effluents, and to investigate its use for other vapor-phase organic compounds.

In a stack simulation study designed to measure sampler temperature, organic compound level, and concentrations of sulfur dioxide, nitric oxide, and water vapor, only the organic compound level had a statistically significant effect on recovery for two of the compounds. In an ambient temperature study measuring sampler temperature, organic compound loading, and relative humidity, none of the variables had a statistically significant effect. The sampler demonstrated a collection efficiency of 100% when operated at or below the design conditions for all but the two most volatile compounds used, and recoveries ranged from 70 to 97% for compounds with high boiling points. *EPRI Project Manager: Charles Hakkarinen*

### The EPRI Water Supply Data Base System

EA-790 Final Report (RP762-1)

The result of this study by the University of Arizona is the EPRI water data base. This research was focused on national and regional data sets that provide information about the Colorado River Basin. The data system has two components: (1) a macro data base that contains overview information about regions, organizations, and data sets and their interrelationships; (2) a micro data base that contains the detailed structure of each data set, information about each set, and method of accessibility. *EPRI Project Manager: Edward Altouney*

### Regional Electric Utility Operations Model National Energy Evaluation System

EA-897 Final Report, Vols. 1 and 2 (RP208)

The Regional Electric Utility Operations Model is an advanced computer simulation of the hourly operation of an electric power generating system, which determines operating expenses, fuel consumption, and environmental emissions associated with a specified plan of generating unit additions. The model, developed by General Electric Co., has the flexibility to consider dollar costs alone or a user-specified, weighted combination of dollar costs and environmental emissions. This new model will facilitate analysis of utility system expansion and operations issues on a regional scale. It complements, rather than replaces, existing production simulation programs that were designed for utility specific generation planning studies. Volume 1 presents the final technical report; Volume 2 is a program usage guide. *EPRI Project Manager: Eugene Oatman*

### Survey of Chlorine Analytic Methods Suitable for the Power Industry

EA-929 Interim Report (RP879-1)

This report contains the results of a study by the University of Maryland of four instrumental-electrochemical and two colorimetric methods for chlorine analysis to determine which ones are most suitable for power plant applications. The methods were an automated amperometric titration, amperometry, membrane probe amperometry, potentiometry, and methods based on the use of DPD and syringaldizine colorimetric reagents. *EPRI Project Manager: Robert Kawaratani*

**Generation System Reliability Analysis for Future Cost/Benefit Studies**

EA-958 Final Report (RP806-1)

What is the economic effect if electric utility customers do not have reliable electric service? The major emphasis of this report by General Electric Co. is on the development of a new method for calculating the frequency and duration of emergency procedures. The ultimate objective of this cost/benefit analysis is to determine the optimal level of reliability by combining customer costs and customer loss of benefits. *EPRI Project Manager: Eugene Oatman*

## FOSSIL FUEL AND ADVANCED SYSTEMS

**Evaluation of 1-MW Horizontal Scrubber**

FP-752 Final Report (RP537-1)

A 1-MW horizontal scrubber system was evaluated by the Tennessee Valley Authority to determine its performance for desulfurizing flue gas obtained from burning high-sulfur eastern coal. Attention was directed toward determination of $SO_2$ removal as a function of various scrubber operating parameters; absorbents tested were sodium carbonate, lime, and limestone. The scrubber was tested in the crossflow and counterflow configurations (liquid flow relative to gas flow). The $SO_2$ removals were lower than expected, possibly due to low slurry retention time in the small scrubber. *EPRI Project Manager: Thomas Morasky*

**Characterization of Mineral Matter in Coals and Coal Liquefaction Residues**

AF-832 Annual Report (RP366-1)

To characterize organic and mineral components of coals and coal liquefaction residual materials, Pennsylvania State University sought relationships between the composition and properties of these components and the behavior of specific coals during liquefaction processes. The characterization techniques included optical and scanning electron microscopy, X-ray diffraction, Fourier transform infrared (FTIR) spectroscopy, and particle-size analyses. The residual materials were found to consist of organic and inorganic components: the organic components comprised unaltered or partly reacted macerals and carbonaceous solids formed by retrogressive reactions during processing; the inorganic components comprised coal minerals, pyrrhotite, and calcium carbonate precipitates. The exact distribution of these components is a function of feed coal and processing conditions (H-Coal or solvent refining). *EPRI Project Manager: William Rovesti*

**Filtration Equipment Development for Coal Liquids**

AF-852 Final Report (RP459-1)

To improve the filtration operation for liquefied coal, an innovative 50-ft$^2$ rotary pressure precoat filter, incorporating many new design features, was designed by Johns-Manville and Stearns-Roger, Inc., and built by Stearns-Roger's General Iron Works. The filter was installed by DOE at Pittsburg & Midway Coal Mining Co.'s solvent-refined coal pilot plant in Fort Lewis, Washington.

Filtration rates over twice those experienced to date at Fort Lewis are expected, with substantial reductions in filter aid consumption and maintenance costs. *EPRI Project Managers: H. H. Gilman and Norman Stewart*

**Magnetic Separation of Mineral Matter From Coal Liquids**

AF-875 Final Report (RP365-2)

An earlier study of magnetic separation of mineral matter from coal liquids (AF-508) has been carried forward by MIT. Treatment of dry residual filter-feed solids with appropriate $H_2/H_2S$ atmospheres increased the magnetization of the solids by an order of magnitude. A parallel treatment of the wet filter feed in autoclave studies has successfully upgraded the magnetization of the suspended solids at process operating temperatures, with a corresponding increase in the magnetic separability of solids, which were originally in a low magnetization state. The investigation indicates that it should be possible to separate all the sulfide and other magnetic solids by employing a $H_2/H_2S$ gas treatment stage at a temperature between that of the liquefaction stage and the preferred magnetic separation state at 221 °C (430 °F). *EPRI Project Manager: William Rovesti*

**Exploratory Studies of High-Efficiency Advanced-Fuel Fusion Reactors**

ER-919 Annual Report (RP645-2)

The objective of this study, being conducted by Brookhaven National Laboratory, University of Illinois, Lawrence Livermore Laboratory, and Florida Power & Light Co., is the examination of the potential advantages and feasibility of using deuterium and D–$^3$He fusion fuels. The second year of the project consisted mainly of the examination of alternative reactor concepts, such as bumpy tori and field-reversed mirrors for use as D–$^3$He satellite reactors. The costing analysis performed on three tokamak reactor designs (a "catalyzed" D reactor, a D–$^3$He satellite, and a comparison D–T machine) indicated the cat-D design was less expensive than the D–T power plant, while the D–$^3$He satellite cost 15% more than the cat-D design. *EPRI Project Manager: David Paul*

**Full-Scale Scrubber Sludge Characterization Studies**

FP-942 Final Report (RP537-1)

The Tennessee Valley Authority and Energy Research Corp. performed chemical, physical, and instrumental characterization studies on 97 samples of sludge and dried solids obtained from five full-scale wet lime or limestone $SO_2$ scrubbing systems. The objective of this project was to provide a data base containing detailed and representative chemical and physical property data from flue gas desulfurization sludges and, where possible, to relate the sludge physical property data to either chemical composition, solids component morphology, or plant operating conditions. Under normal (reducing) conditions, the solids component of scrubbing slurries consisted predominantly of calcium sulfite hemihydrate and fly ash, while sulfite was present as single-plate crystals when limestone was used as the absorbent and as complex spheroidal aggregates when lime was used. *EPRI Project Manager: Thomas Morasky*

**Implications of the Fusion Power Source to the Electric Utility Industry**

ER-943-SY Summary Report (WS-77-16)

This report, edited by Nichols and Associates, Inc., describes the mutual examination of viewpoints and plans of the utility industry and the fusion community that took place in October 1977 at the EPRI Executive Seminar on Fusion. The workshop concentrated on providing the participants with the basic background material concerning the fusion process, including discussions of the current status and future plans of the fusion research and development effort. *EPRI Project Manager: Robert Scott*

**Examination of Specific Aspects of Cooling-Tower Testing Methodology**

FP-953 Final Report (RP905-1-2)

Specific aspects of improved testing methodology (including instrumentation and instrumentation deployment) for closed-cycle evaporative cooling systems were addressed by Environmental Systems Corp. Included are an investigation into the accuracy of instruments used for determination of wet-bulb temperature; an examination of cooling-tower capability calculations based on wet-bulb temperatures measured as the air enters the cooling tower (versus at ground level, upwind of the tower); and a study of water flow rate determination, using nonreinforced and reinforced pitot tubes. To accommodate multiple-point inlet wet-bulb temperature measurements, a data acquisition system using platinum resistance temperature devices as sensing elements proved to be efficient. *EPRI Project Managers: John Bartz and John Maulbetsch*

**Development of an Extruder Feed System for Fixed-Bed Coal Gasifiers**

AF-954 Final Report (RP357-1)

An extruder developed by General Electric Co. was demonstrated, feeding 1 t/h of a ground coal and by-product tar blend into a pressure vessel at over 2 MPa (20 atm) gas pressure. Once at pressure, the resultant coal extrudate was fractured into lumps suitable for gasification in a fixed-bed reactor. In the process, coal ground to <1/8 in was blended and heated with by-product producer tar to about 93–120°C (200–250°F), and then was conveyed and fed to the extruder.

The system demonstrated attractively high sealing ability, high output, low power requirement, and acceptable metal wear, feeding coal against 34 MPa (500 psi) hydrostatic backpressure, 21.2

MPa (325 psi) air backpressure, and 7 MPa (100 psi) producer gas backpressure. *EPRI Project Manager: Linda Atherton*

**Advanced Technology Fuel Cell Program**

EM-956 Annual Report (RP114-2)

Molten carbonate fuel cells, advanced phosphoric acid fuel cells, advanced fuel processors, and the use of coal and coal products in central stations or dispersed fuel cell power plants are being investigated in RP114-2, which was carried out in parallel with activities funded by the contractor, United Technologies Corp., to define materials, configurations, processes, and power plant designs. During this report period, a subscale molten carbonate cell achieved 15,370 hours' endurance with stable performance through 13,000 hours. Posttest analysis showed the anode structure was stable, but shutdown of the cell resulted from edge seal corrosion (an improved seal has been demonstrated through 5000 hours of corrosion tests and 1150 hours of cell tests). Over 80% of improved subscale cells now show no internal leakage after 1500 hours' operation, compared with $<20\%$ of cells with no leakage at the beginning of the report period. Studies of dispersed power plants using the molten carbonate fuel cell indicate that units based on truck-transportable modules can meet EPRI goals of 7500 Btu/kWh heat rate and \$350/kW when operating on liquid fuels from coal or petroleum. *EPRI Project Manager: Arnold Fickett*

## NUCLEAR POWER

**Transient Deformation Properties of Zircaloy for LOCA Simulation**

NP-526 Final Report, Vol. 5 (RP251-1)

The creep/creep rupture anisotropic properties of Zircaloy were determined and compared by analytic technique with ramp pressure and ramp temperature test results. The combination of test results and predictive analysis techniques shown in this report by Battelle, Pacific Northwest Laboratories provides a means to predict the transient deformation of reactor fuel cladding during simulated LOCA conditions. Results include creep/creep rupture strain numerical constitutive relationships out to 120 seconds, computer codes, and ramp test rupture data. *EPRI Project Manager: Adrian Roberts*

**Planning Support Document for the EPRI Nondestructive Evaluation Program**

NP-900-SR Special Report

This special report describes the framework in which EPRI's Nondestructive Evaluation Program was established and is being implemented. Details on specific inspection problems are given, as well as the technical approach being followed and planned future activities. An appendix provides a summary of each project under way or completed. *EPRI Project Managers: Gary Dau and Karl Stahlkopf*

**Nuclear Pressure Vessel Steel Data Base**

NP-933 Topical Report (RP886-1)

Pressure vessel steel data amassed in EPRI research programs since 1974 have been collected by Fracture Control Corp. in a computer data base, which includes heat descriptions, manufacturing and fabrication information, chemistry, temperature-dependent regression analyses (tensile, Charpy, and precracked Charpy), and regression statistics. The main text of the report describes the data base and provides detailed explanations and examples of the tables and graphics. Seven appendixes present the data on a heat-by-heat basis. *EPRI Project Manager: Theodore Marston*

**Studies of AISI Type-304 Stainless Steel Piping Weldments for Use in BWRs**

NP-944 Final Report (RP449-2)

In an investigation by General Electric Co. the objectives were to identify and to quantify the effect of the state of stress and the state of sensitization that exist in as-welded, type-304 stainless steel piping on the intergranular stress corrosion cracking behavior of small- and large-diameter piping systems and to determine the difference in service performance. The results of this 2½-year program and a mechanistic interpretation of the causes of cracking are presented in this report. *EPRI Project Manager: Richard Smith*

**Nonlinear Soil-Structure Interaction for Nuclear Power Plants Subjected to Earthquake Excitation**

NP-945 Final Report (RP810-2)

Weidlinger Associates developed models of constitutive properties of soil and soil-structure interaction for nuclear power plants in earthquakes to simulate a three-dimension structural geometry, nonlinear site characteristics, and arbitrary input ground shaking. Cyclic hysteresis in shear was accounted for by adding viscoelastic behavior as an interim step and by permanently amending the cap model to include nonlinear kinematic hardening in shear; the cap model was extended to include the effects of pore fluid on the seismic response of soils. The soil island approach to soil-structure interaction was applied to the Simquake-I series of explosive field tests designed to simulate earthquake ground motion effects on model nuclear containment structures. Two- and three-dimension finite element simulations of the tests were performed, and results were compared with measured data. Pretest indications of the Simquake-II event were made with two- and three-dimension nonlinear soil island models, the three-dimension model yielding lower response than the two-dimension one. *EPRI Project Manager: Conway Chan*

**Radiation Source Terms in LWR and LMFBR Spent Fuel**

NP-948 Final Report (TSA78-156)

A new method was developed by Science Applications, Inc., for calculating average energies of external bremsstrahlung radiation induced by continuous beta spectra in thick media. Results are presented of calculations of beta and gamma aggregate fission-product source terms in LWR and LMFBR spent nuclear fuel at storage times of up to 20 years. The beta source terms are in the form of spectral-averaged energies, while the gamma source terms are in the form of both eight-group energy spectra and total-decay energies. *EPRI Project Manager: Frank Rahn*

**Characterization of Corrosion Products on Recirculation and Bypass Lines at Millstone-1**

NP-949 Interim Report (RP819-1)

This report by General Electric Co. describes corrosion products found on portions of the recirculation loop bypass lines and a flange from the recirculation line of Millstone-1. A duplex structure identified for the corrosion scale consists mainly of a loosely adherent outer layer of $\sigma$-$Fe_2O_3$ and a tightly adherent inner layer to which a spinel structure can be assigned. The distribution profile of several elements across the inner layer was determined by ion microprobe analysis and a model for crud growth is proposed. *EPRI Project Manager: Robert Shaw*

**Utilization of Real-Time X-Radiography for In-Service Inspection of Nuclear Reactor Piping**

NP-950 Final Report (RP607-2)

Science Applications, Inc., made real-time radiographic (RTR) inspection of two 4-in-diam schedule-80 BWR pipes obtained from General Electric Co. One sample pipe was specially machined with slots of known dimensions to determine the absolute sensitivity of the real-time system; the second pipe contained actual intergranular stress corrosion cracks to determine the relative sensitivity of real time compared with a fine-grain X-ray film. The results of the study indicated that the real-time radiography system could resolve simulated cracks 0.008 in wide, 0.030 in deep, and 0.010 in wide, 0.015 in deep, indicating a thickness sensitivity of 4.4 and 2.2%, respectively. Crack detection abilities were comparable with the AA X-ray film; however, the film provided a more detailed image of crack patterns.

RTR in-service inspection has the advantages of immediate presentation of image and an enhanced probability of crack detection because the system can be rotated about a pipe to seek optimal crack orientation. *EPRI Project Manager: Gary Dau*

**An Endochronic Constitutive Model for General Hysteretic Response of Soils**

NP-957 Final Report (RP810)

A new endochronic theory of plasticity, which accurately describes the mechanical response of hysteretic materials to complex, three-dimension deformation histories, including cyclic deformation, is presented by Systems Science & Software. Various features of the resultant model include an ability to describe cyclic simple shear of dry sand and wet clay over many cycles of deformation, response of a real soil to standard laboratory soil tests, and response of soil to cyclic triaxial tests. This model can be applied to other materials, such as metals, and could provide improved descriptions of the response of various metallic components under transient loads. *EPRI Project Manager: Conway Chan*

**A Computer Model for Ductile Fracture: Applications to the Charpy V-Notch Test**

NP-961 Interim Report (RP603)

This computer model developed at Lawrence Livermore Laboratory predicts fracture toughness from Charpy and tension tests with standard surveillance specimens. The fracture model is based on plastic strain; fracture starts or a crack extends when the integrated product of the equivalent plastic-strain increment and a function of the mean stress exceeds a critical value over a critical length, which is characteristic of the microstructure of the material. The model predicts fracture initiation and flat propagation in the standard Charpy V-notch specimen. *EPRI Project Manager: Theodore Marston*

**Analysis of Steam Chugging Phenomena**

NP-962 Interim Report, Vols. 1, 2, 3 (RP1067-1)

A thermal-hydraulic model has been developed by Jaycor to describe steam chugging phenomena that may occur in LWR pressure suppression pools. Volume 1 describes calculated results, use of the new model, and a variety of measured chugging parameters obtained from small-scale experiments. Volume 2 is a user's manual for the CHUG-1 computer program, which uses fundamental thermal-hydraulic models to describe steam condensation phenomena. Volume 3 describes a free-surface hydrodynamic code developed to study the fluid response in steam suppression systems during chugging events; the methods employed include the partial-cell treatment of the free surface and the time average and central difference numerical schemes for solving the equations of motion. *EPRI Project Manager: Jean-Pierre Sursock*

**Workshop Proceedings: Flow-Induced Vibration**

Workshop Report (WS-78-125)

This workshop on flow-induced vibration, principally in the area of nuclear reactor steam generator design, was attended by representatives of major nuclear-reactor-related companies and research laboratories. The objectives of the work shop were to identify the unresolved problems of flow-induced vibration in steam generator design; outline the state of the art; and define work required to eliminate unknowns and provide further understanding of flow-induced vibration phenomena and their ramifications as related to steam generator design and operation. A summary of each participant's presentation is given, together with each participant's presented material and an extensive list of developed references. This report is available without charge from EPRI. *EPRI Project Manager: David Steininger*

ELECTRIC POWER RESEARCH INSTITUTE
Post Office Box 10412, Palo Alto, California 94303

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