Geothermal Energy–The Hot Prospect

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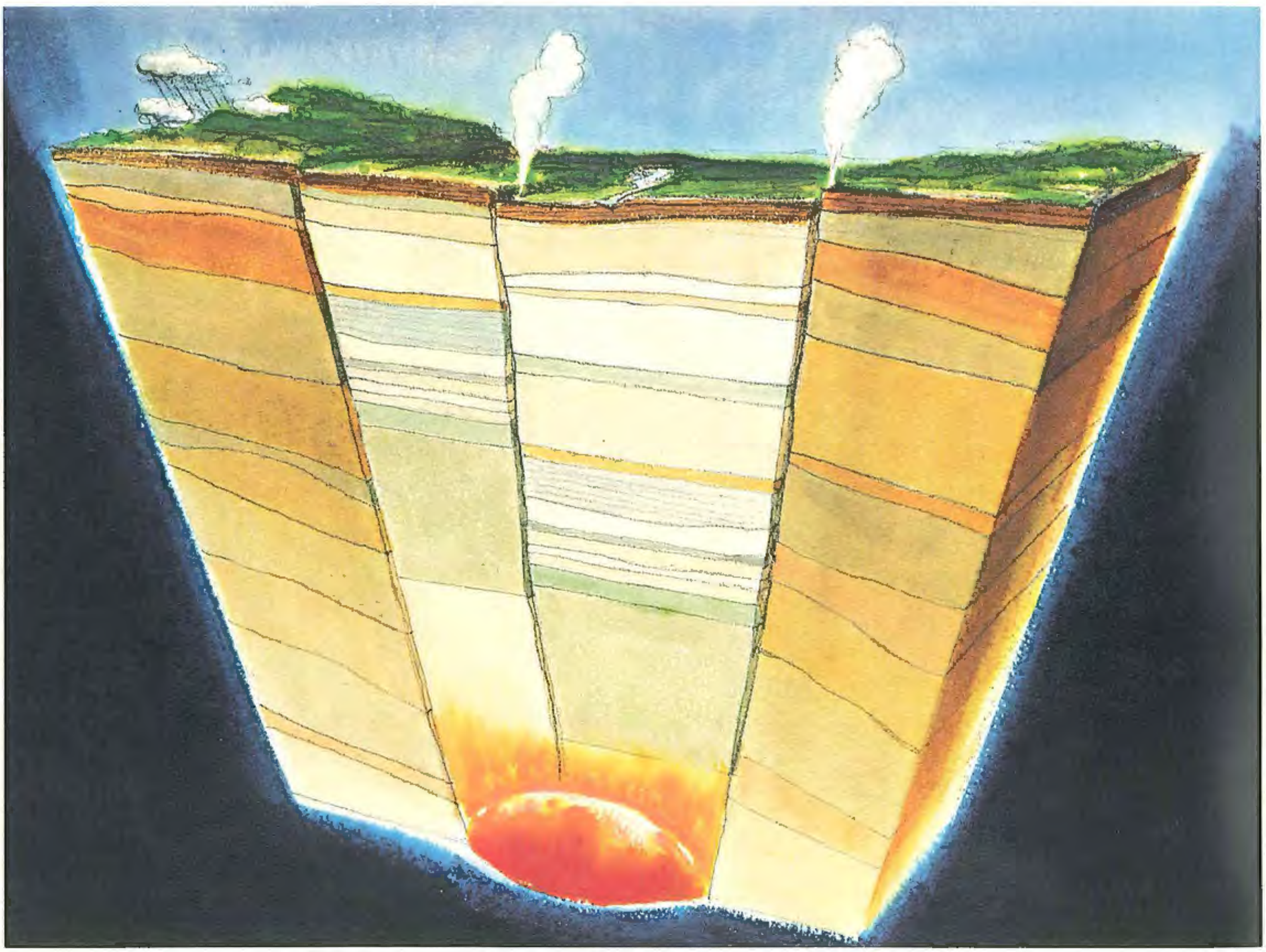

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Cover: Telltale plumes of geysers and hot springs signal a geothermal area. This gigantic plug, cut from the earth's crust, has its own weather system above, magmatic intrusion below, and fault-fractured geothermal reservoir in between.

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R&D for Electric Utilities: Cost-effective for the Ratepayer

During March, a contingent of senior EPRI officials "went on the road" to report on the Institute's program and accomplishments to the electric utility industry. Regional meetings took place in seven cities. The following is a condensation of remarks made by Dr. Starr at those meetings.

The real justification for a large electric utility R&D program is its potential for holding down capital and operating costs. The effort will help provide electricity at reasonable costs to consumers.

EPRI's R&D program can maintain the industry's technical ability to respond to future external pressures that are certain to develop. These developments can be as mild as a subtle shift in consumer use patterns or a small increase in fuel costs, or they can be as severe as restrictive legislation or regulation or the loss of a basic fuel source. Few other industries are as susceptible as this one is to forces beyond its control. The result can be a substantially increased financial burden on its customers. R&D can reduce this susceptibility.

The industry is likely to be tested in a number of ways in the years ahead. The fossil fuel supply situation is a puzzle at best. Not much more is known about the shape of coming regulations governing the burning of these fuels, but all indications are that they will be more restrictive. The future of nuclear power is still a subject for speculation, with the long-range outlook for the light water reactor somewhat less fuzzy than that for the breeders. Most disquieting is the uncertainty in the future demand for electricity and attendant issues, such as economic growth, conservation, and broad environmental questions.

To say, in the face of this, that the industry is looking at moving targets would be doing injustice to a truly bewildering set of unknowns. Creating a single plan to deal with these contingencies is a virtual impossibility because of the variety of conditions that need to be anticipated, their different intensities, and very major questions of timing. So rather than a set plan, the need of the utility industry is for flexibility and adaptability, alternative choices, or more specific to R&D, a set of technical options.

There are many examples, but one that makes the point as well as any is the coal situation. Do any of us really know how much and in what form we will be able to use this most plentiful resource? We face a long list of variables on that question—some are technical, some are economic, some are environmental, and some have more to do with other industries and other fuels than with coal. How many of these variables can the electric utility industry influence? Unfortunately, the industry's role must be a partially passive and reactive one.

But our preparation today for the answers to these questions tomorrow needs to be anything but passive and reactive. Working through EPRI and its own facilities, and cooperatively with government research organizations, the industry is mounting a coal-related R&D campaign on a broad front. This work should put electric utilities in a position of readiness for the time when the curtain is slowly drawn open and the destiny of coal finally becomes visible.

In the meantime, we must move with optimistic vigor on scrubber development, even though there is no assurance that scrubbers will be the answer. We must move on gasification technology and on liquefaction technology, even though there is no guarantee that therein lies the way. And we must move on technologies that will allow utilities to burn coal directly in environmentally acceptable ways, even though the same uncertainty applies.

I am not suggesting that we play research roulette. The reality we face is that any promising technology has so many operating and economic question marks that reliable predictions of its commercial feasibility are impossible. We cannot afford the luxury of putting a single favored technology in the race now with the assumption that other entries can be added if the leader should falter. Development times are too long to allow this luxury. We need to make a thoughtful selection of strong technological candidates and bring them all along as fast as the R&D process allows. The future economic value of our national R&D could be mostly lost if we cut down our options by trying to crystal-ball the outcome of each long and arduous effort.

Consider the similarity between R&D and preventive maintenance. Both require planning, both require a budgeted outlay, and both have their roots in the need for continuity of efficient and economical operation. And while maintenance programs help mitigate the effects of physical depreciation of equipment, R&D helps guard against technical depreciation in a technology-based industry. Finally, it should be kept in mind that maintenance, like R&D, can be deferred with no immediate effect on the system's ability to deliver electricity. The benefits of both activities lie in the future, as do the serious economic consequences of delaying them today.

EPRI is cost-effective for the electric utility customer, and that is the ultimate measure of any electric utility expenditure. The Edison Electric Institute reported recently that investor-owned utilities alone plan to spend $122 billion on new plants and equipment in just the next five years. In that same time period, EPRI will be spending less than 1% of that amount on programs that will maximize the effectiveness of those major capital outlays.

It comes down to the issue of whether the electric utility industry can afford to gamble on meeting tomorrow's needs with today's conventional technology. To the degree that this is not economically wise, the industry's support of EPRI will continue to meet the test of prudent business.

C Starr

Chauncey Starr
President
Electric Power Research Institute

The future is what EPRI is all about. Even so, the same as anyone else, EPRI and its people can slip easily into a narrower frame of mind that looks only at yesterday, today, and tomorrow: the advisory committee meeting attended, the contractor's progress report under review, the new project authorization to be sought.

The future comes sharply to mind, however, in reviewing the articles in the JOURNAL this month. Regional and national implications and consequences, not tomorrow but one or more decades from now, are more than usually evident.

□ **"Geothermal Energy—The Hot Prospect"** (page 6), for example, could be the new source of 40,000 MW on-line in the year 2000. It's just now moving out of the category of exotics and into the conventional.

The new outlook is the result of increasing experience. Until recently, the absence of experience has been a subtle check on even the most farsighted developers and utilities. This is one impression gained by JOURNAL feature editor Ralph Whitaker in developing this month's cover article. Whitaker's sources, starting with Vasel Roberts, EPRI's program manager for geothermal energy, included assessments of worldwide geothermal development and an inventory of U.S. potential.

But though geothermal experience may yet be scant, technology is not. This is another impression, gained from EPRI-sponsored reports that lead to an upcoming hydrothermal demonstration plant. Resource assessment, for example, has benefited immeasurably from geochemical thermometry, the determination of reservoir temperatures from the chemical and ionic composition of fluids and their rates of change and precipitation.

In sum, geothermal technology has moved quickly, hitchhiking at times with geology and other sciences. Geothermal experience is still at the low end of the curve, but the slope is increasing and there shouldn't be any inflections in the next 25 years.

□ The future for U.S. energy policies, as for many other national affairs, has been symbolized in these early months of 1977 by the new President and the new look he has brought to Washington. That look includes **"Joseph Fisher: An Energy Leader in Congress"** (page 14). Just elected to his second term, Fisher is also a member (and former chairman) of EPRI's Advisory Council and a professional economist. He brings all those roles together in this interview by Barry Sulpor, manager of the EPRI news bureau.

□ The further we go into the future, the more our growth and interdependence encourage large technological systems. The U.S. energy network is one such system. It is undeniably valuable; it confers benefits. It is also costly; it entails risks. Responsible development therefore calls for conscious evaluation of **"Energy and Environment Trade-Offs"** (page 18).

Staff writer Stan Terra's article looks into the subject of risk-benefit analysis, especially the practice of technology assessment and the major components of technological impact. Terra reviews a recent book that features three EPRI names: President Chauncey Starr keynoted the 1974 seminars that became its chapters; planning director Ric Rudman and planning staff member Chris Whipple were two of its editors.

□ The future use of coal as a boiler fuel, whether we treat it or convert it or just clean up its combustion products, occupies a lot of professionals in R&D. The context is simple: There's more coal than oil and gas, so we have to make the switch.

But time is limited and we may be facing fuel shortages. In **"Coal Conversion—A Partial Answer"** (page 22), **George Hill** suggests how oil- and gas-fired power plants themselves can help us make the transition.

George Hill has been helping coal along for most of his career. Now director of the Fossil Fuel Power Plants Department in EPRI's Fossil Fuel and Advanced Systems Division, he previ-

Hill

Gilman

ously headed the Office of Coal Research in the U.S. Department of Interior. For 26 years before that he was on the faculty of the University of Utah, 15 years as founding chairman of the Fuels Engineering Department and 6 years as Dean of the College of Mines and Mineral Industries.

▫ The JOURNAL's technical feature this month puts another twist on the subject of coal—not as a substitute for oil but as an additive to help it go further. The author is **H. H. Gilman,** engineering manager for EPRI's Advanced Fossil Power Systems Department.

After graduating from Stanford University in mechanical engineering, "Pete" Gilman spent over 25 years with refineries, designing subsystems and support facilities; supervising design, engineering, construction, operation, and maintenance; and troubleshooting. His early work with Standard Oil Co. of California and its subsidiaries led to a 20-year association with American Gilsonite Co., ultimately as division manager in charge of a Colorado refinery.

With that kind of experience, Gilman prefers research of the "hands-on" kind. A good example is the innovative tinkering needed in adapting boilers and burners to test **"Coal-Oil Emulsions for Boiler Fuel"** (page 56).

GEOTHERMAL ENERGY— THE HOT PROSPECT

Natural heat inside the earth is a long-lived energy source. We generate electricity now with steam from geysers, and soon we'll do it with hot water from geothermal wells.

An EPRI state-of-the-art feature

Look down. Beneath your feet there is geothermal energy, the earth's interior heat, constantly leaking out in elusive patterns and varied forms. Some we have already harnessed, some we will never capture. But can we categorize it, even for the U.S. alone, and can we define and evaluate the amount that might be useful for generating electricity?

The answer is yes, and the task was authoritatively begun with U.S. Geological Survey efforts reported just two years ago. But there are some important conditions:

- First, consider only the geothermal reservoirs hotter than 150°C (that's 300°F and pretty much the lower limit for an efficient steam cycle)
- Second, set aside all questions of how to extract the heat (it will tax our ingenuity to sink a well into magma!)
- Third, completely disregard cost

On these bases, the U.S. geothermal resource is equivalent to about 450,000 MW, just a little less than the total U.S. generating capacity today.

Scaled down to include only the steam and hot water that could be tapped by methods known today, but still without regard to cost, the resource is a respectable 46,000 MW.

Developed geothermal capacity, however, stands in distinct contrast: 502 MW, all of it belonging to Pacific Gas and Electric Co. (PG&E) at The Geysers in California, produces about 0.2% of our electricity, or less than 0.0006 of all U.S. energy consumption.

Vasel Roberts, EPRI's program manager for geothermal energy, prefers to look through the funnel from the other end. "The important thing right now," he says, "isn't how big a resource base there is, but how well we are putting to use our known reserves—the geothermal energy we can extract economically with today's knowledge and equipment."

On this basis we're doing well. From 11 MW in 1960, PG&E's capacity at The Geysers grew to 290 MW by 1972. Two plants of 106 MW each were later added, raising the total to 502 MW in 1975. Three more units are now being built, and capacity at The Geysers, by PG&E alone, is planned to hit 2000 MW by 1987, quadrupling the 1975 figure in just 12 years.

Four prospects

The most vivid understanding of geothermal energy comes from distinguishing its different physical forms, why and how they occur, and their relative importance.

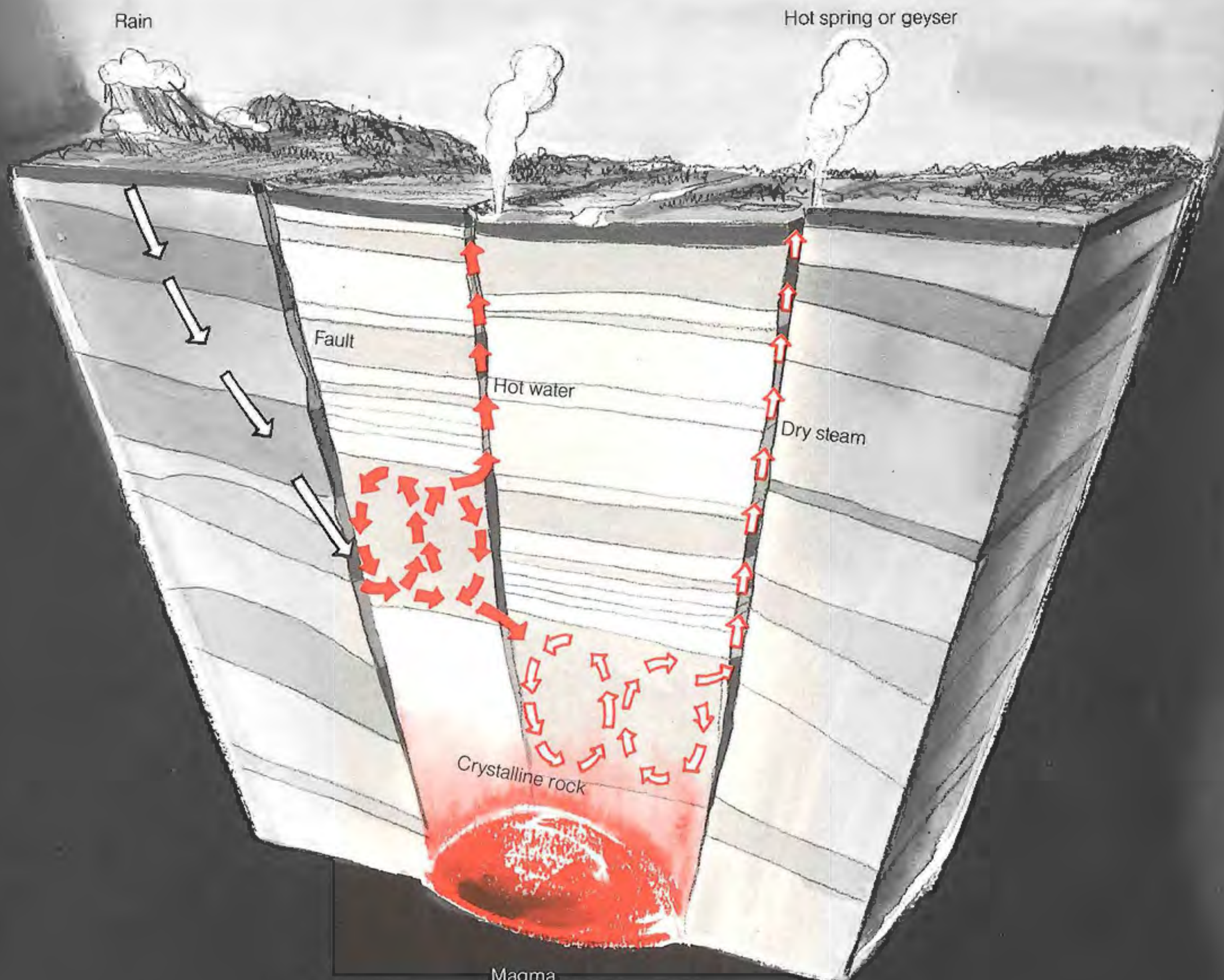
Dry steam is the most obvious, easiest to use, and rarest geothermal form—some say less than 0.5% of the usable potential. Whether tapped by a well or occurring naturally in a geyser, this geothermal fluid flows to the surface under pressure or is flashed to vapor as it rises.

Hot water is the next most attractive form—20 times the amount of steam, or perhaps 10% of the resource. Where it is under pressure, it may be as hot as 360°C, well above geothermal steam. Both fluids exist at accessible levels and useful temperatures because of convection currents that gradually transfer heat upward from its source, the hot rock (and sometimes magma) squeezed into fractured portions of the earth's hardened crust. The water in these systems originates as rainfall runoff that percolates down over very long time spans and sometimes over great horizontal distances. It is not known whether steam and hydrothermal resources are renewable, because fluid extraction on a time scale of years inevitably upsets the natural cycle of heat supply and dissipation, which is on a geologic time scale.

Geopressured systems are a very different type, but at an estimated 20% of U.S. geothermal resources, they are potentially important. They consist

Convection loops in geothermal reservoirs are the last stage in the natural migration of heat outward from the earth's molten core, where they are also the initial stage. In unbroken portions of the earth's crust, heat is transferred by conduction, a slow and diffuse process revealed by gentle temperature gradients that decrease toward the earth's surface.

But where that surface is weakened, as by the fractures and faults at crustal plate boundaries, magma intrudes – a hot mass transported from below. Geothermal heat is thus concentrated in geologically active regions. Hydrothermal convection cells transfer the heat up, where it vents naturally in hot springs, fumaroles, or geysers – or to a level that is accessible for extraction through wells.



of water from 150°C to 200°C (and usually dissolved methane) trapped in sediments by overlying impermeable shales. These reservoirs lie under the U.S. Gulf Coast and offshore, where they were formed by the successive deposition of sediments that account for their depth (below 3 km) and pressure (thousands of pounds at the wellhead). Oil exploration has thoroughly mapped the extent and cap depth of the geopressured regions, but records of geothermal yield are scant because drillers have not produced from these strata.

The largest geothermal prospect—some 70%—is crystalline rock and magma, together classed as hot igneous material. Magma is the hotter medium, having originated at great depth and then intruded into the crust above, causing volcanic activity. It is frequently an intermediary in the transfer of interior heat into steam and hydrothermal convection cells.

Pattern of origins

The link between volcanic activity and useful concentrations of geothermal heat is basic. If the earth's crust were uniform, so also would be the transfer and dissipation of heat outward through it to the surface. But this order and symmetry are moderately altered by variations in the thermal conductivity of different rocks and strata, and they are sharply distorted by the occurrence and effects of tectonic and volcanic activity.

Tectonic has to do with crustal deformation and the forces behind it. On a world scale, the geologist's concept of tectonic activity postulates crustal segments, or plates, that move, implying boundaries (faults) between them where they part or where they meet. (Interestingly, one fundamental geologic view holds that multiple convection cells in the earth's plastic mantle produce upward and outward flow and that this is the essential mechanism causing lateral movement of the continental and oceanic plates.) Specific occurrences of fracture or dislocation constitute seismic activity, and they create the weakened zones where volcanic activity is most likely to occur.

Geologic and geothermal mapping thus coincide. Crustal plate boundaries throughout the world also mark the regions of active or recent volcanism, of faulting, of earthquakes and their epicenters, and of geothermal resources (other than geopressured). The fractured state of crustal rock provides access for percolating water, which becomes the geothermal fluid convecting heat upward and outward throughout a reservoir or field.

The boundaries where plates are formed and from which they move apart are called spreading ridges (or rifts). With few exceptions, they are in the oceans. Where plates meet, one generally sinks beneath the other. These active boundaries are called subduction zones, and they exist mostly at the edges of continents.

Pattern of development

To catalog the world's geothermal resource base, or even its known reserves, has little meaning. Data are incomplete and inaccurate, and development depends on many criteria that are not consistent worldwide. But it is instructive to assess major capacity and thus learn the locations and applications of geothermal heat.

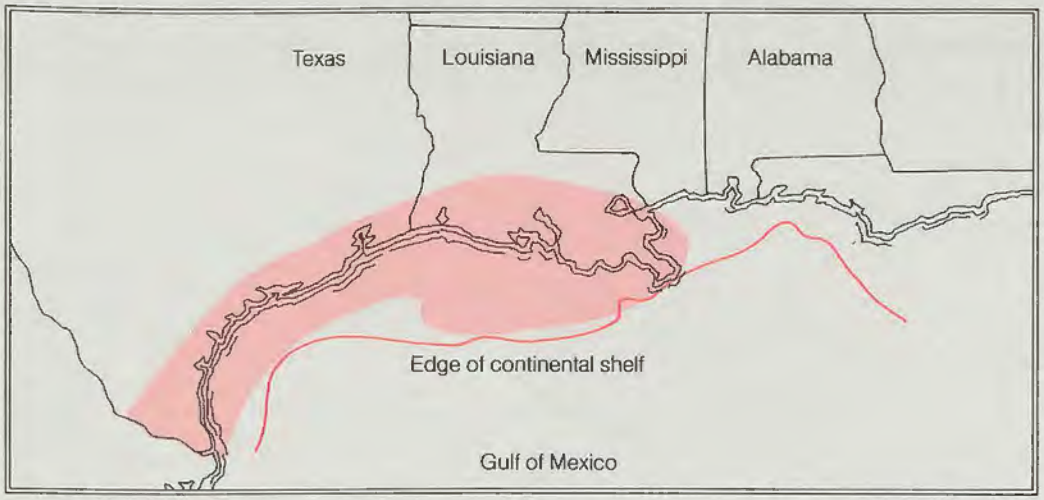
Larderello, Italy, is the field developed longest and one of only three sites in the world producing commercial dry steam. (The others are The Geysers in California and Matsukawa in Japan.) Recovery of boric acid from mineral waters at Larderello dates at least to 1804; use of geothermal steam as heat began somewhat later. Electricity generation, first tried in 1904, has been continuous since 1913 and capacity now exceeds 395 MW.

Iceland began using hydrothermal energy for municipal heat in the 1930s. It was first used in the city of Reykjavik, but now it is used by over half the

Geopressured fluids are contained in sediments buried deeply and quickly—in geologic terms—by further deposits from rivers and the progressive sinking of the U.S. coast along the Gulf of Mexico. Impermeable shales seal these reservoirs, and overlying strata compress them, creating thousands of pounds of pressure that can lift the hot water to the surface and also be harnessed to produce power. Methane dissolved in the geopressured water is thought to be an important fraction of this energy resource. If recovery is ever to be economically attractive, it will depend on the combined value of the methane and the geothermal energy.

Major geothermal regions of the world coincide with crustal plete boundaries. Most of the spreeding ridges or rifts where plates move apart are beneath the oceans: the European, African, and both American continents are slowly retreating from a rift that splits the Atlantic floor south of Iceland. Boundaries called subduction zones, where plates come together and slide over and under each other, rim the continents of the Pacific Ocean.

The Gulf of California marks an unusual juxtaposition of plate boundaries. Here a rift "comes ashore" under the Colorado River delta and the Salton Sea trough just northwest of it—in a region where crustal plates also collide. Thus the southwestern United States represents a complex geologic dynamic and at the same time a rich and widespread geothermal resource.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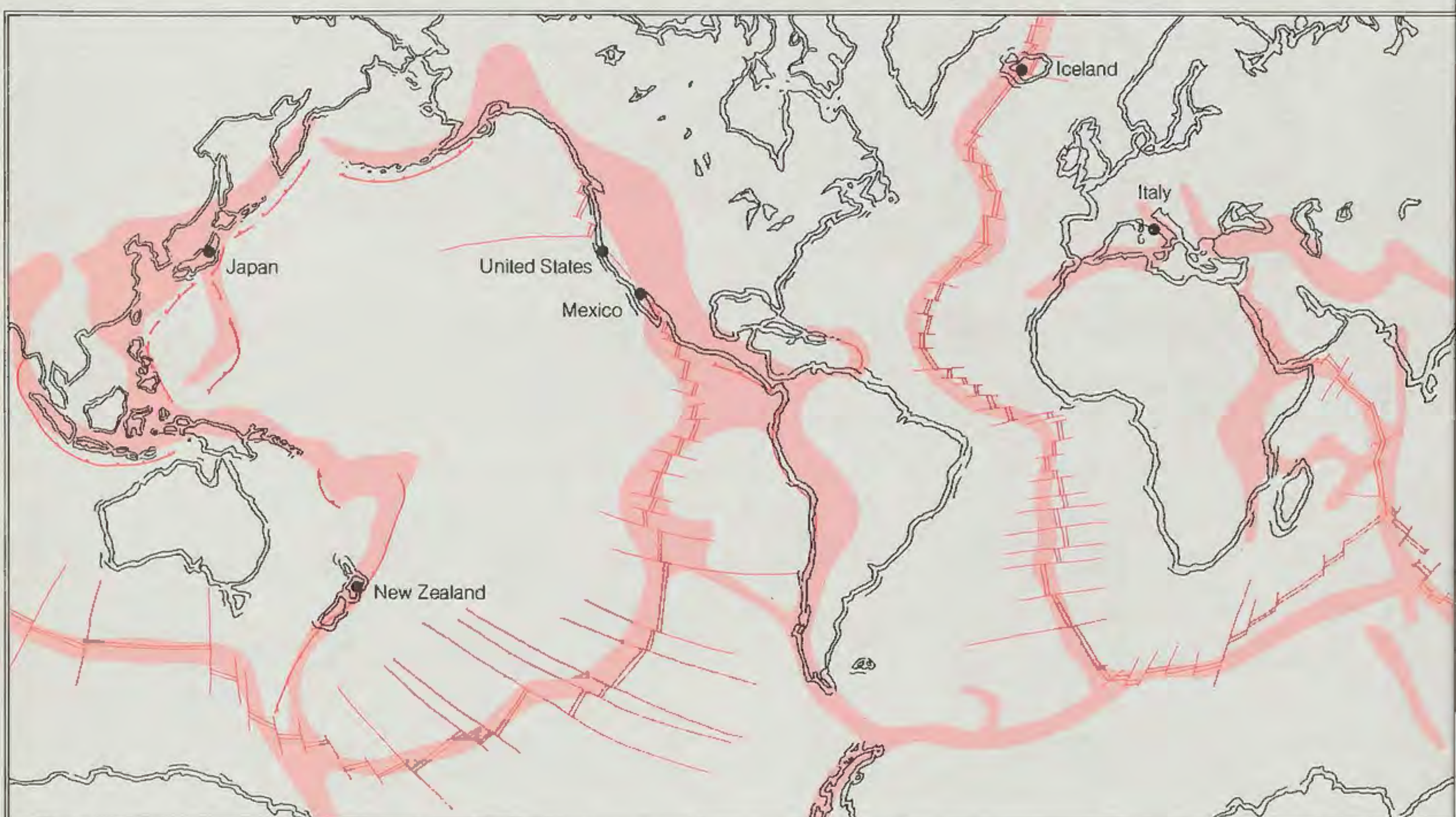
Edge of continental shelf
Gulf of Mexico


Iceland
Italy
Japan
United States
Mexico
New Zealand

nation. Remarkably low mineral content of the water (distributed at 80°C) simplifies the operation and maintenance of the system. Geothermal fluids are used in a lesser way for industrial process heat and to generate electricity.

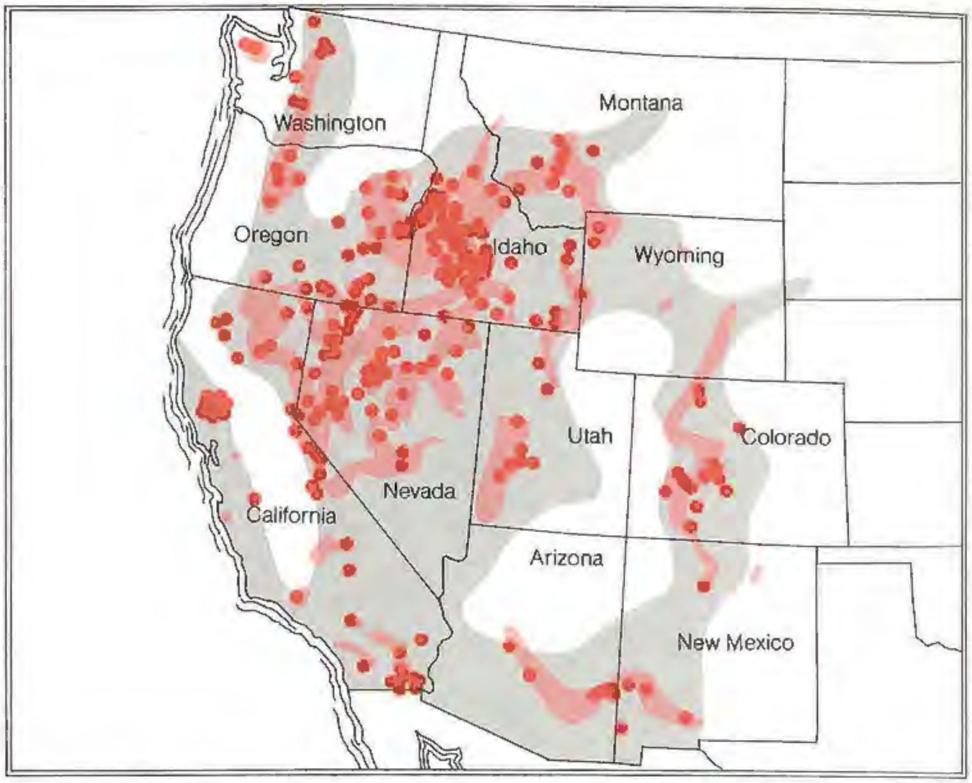
New Zealand's hydrothermal resources have been developed since the 1940s. Generating capacity at two sites totals 202 MW, and steam and hot water are also used to process wood pulp, to run mill machinery, and for heating. Additional geothermal power capacity had been planned, but natural gas discoveries changed the course of development.

Japan's geothermal electric capacity so far remains small, even though experimental generation began in 1924 (and there had been direct use even earlier). Since World War II, experiments and exploration have led to many small applications: 30 kW for a hotel on Honshu, 20 MW for a utility on Honshu, 13 MW for a utility group on Kyushu. Developments continue to be widespread, but most of the energy is directly used in therapeutic and recreational baths and for some agricultural purposes.

Most geothermal energy exploitation has taken place in the industrially developed nations, but exploration now covers a surprisingly wide spectrum: Chile, China, El Salvador, Ethiopia, Guadeloupe, Hungary, Indonesia (volcanic heat was suggested on Java in 1918), Kenya, Mexico, Nicaragua, Philippines, Taiwan, Turkey, USSR, and Zaire. Another 30 countries have begun to gather data or otherwise show interest.

North American focus

Mexico's latest geothermal power development, 75 MW at a plant just below the California border, overshadows all other foreign geothermal capacity in its implications for the U.S. Cerro Prieto, in operation since 1973, lies at the south end of the geothermal zone overlain by the Imperial Valley and Salton Sea. Each of its 15 production

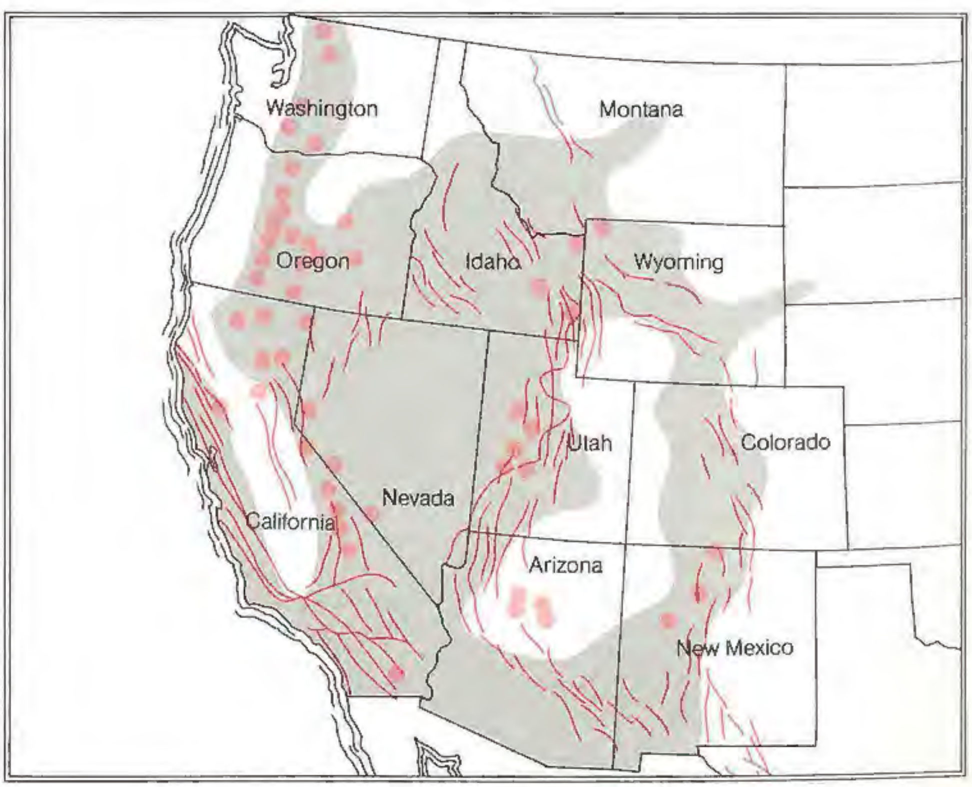


General extent of western U. S. hydrothermal resources is revealed by the coincidence of geothermal (top) and tectonic (bottom) indicators on maps of the region.

At top, colored dots mark the locations of most hot springs and wells. The isothermal contour of 120°F (49°C) surface spring temperature includes all of those sites and also takes in significant additional area.

At bottom, colored dots mark volcanoes. For simplicity, faults of all types are shown by just one style of colored line.

Hydrothermal resources of Yellowstone and Lassen Volcanic National Parks won't be developed, and a large area in southwestern Idaho is conjectural because of its apparent low temperature. Scattered hydrothermal convection systems elsewhere in the 48 conterminous states will remain uneconomic for some time to come because of their great depth.



wells averages 230 Mg/h of superheated brine from reservoirs of more than 300°C at an average well depth of 1.5 km. About 20% of the brine flashes to steam for power plant use, so the average well is equivalent to about 5 MW.

Cerro Prieto is important to U.S. research and development partly for what it reveals about an essentially shared geothermal resource in the Salton Sea trough, the northern end of the rift between Baja California and the rest of North America. It is important also to utilities for its operating experience in handling corrosive brine and in dealing with environmental consequences, mainly from the discharge of waste heat, chemicals, and brine.

Thus, the southeastern California desert, north of the Mexican border, has high priority among geothermal reserves for new exploitation, even though developed capacity at The Geysers will dominate for many years.

Imperial Valley developments began, in at least one case, as early as the 1930s, when shallow (150 m) wells were drilled at Niland to obtain carbon dioxide gas. The value? Production of dry ice to refrigerate rail-shipped produce from the area's year-round truck farms. In later years both potassium chloride and calcium chloride were recovered from Niland's geothermal brines, and 3 MW were generated in an experiment early in the 1960s.

Systematic assessment

In contrast to the The Geysers, a localized dry steam field that may total 2200 MW, with equal hydrothermal potential nearby, the Imperial Valley is thought to have twice that development potential—approximating 9000 MW. Such is the incentive for a geothermal resource assessment that has been systematized and expanded in recent years to include all 11 western states.

Most comprehensive is a 1975 report by the U.S. Geological Survey, notable for its estimates of volume and heat content for 290 steam and hydrothermal systems—258 of which are in those same western states (and 32 in Alaska and Hawaii). By their detail and internal consistency, the USGS figures supersede various earlier geothermal resource estimates that differed by two orders of magnitude—that is, by 100 times! Converted to electricity generating capacity that might be realized with current technology, the major available hydrothermal systems tabulated by the USGS represent about 8000 MW for 100 years (8000 MWcen). This total omits Yellowstone and Lassen Volcanic National Parks and the vast but apparently low-temperature Bruneau-Grandview system in southwestern Idaho, all of which would add another 9000 MWcen.

This time-based measurement—the unit called a megawatt-century—envisions a subterranean reservoir that is emptied of its recoverable heat, without any replenishment during 100 years. It is conservative in that it makes no allowance for heat recharge, the natural inflow and warming of new groundwater, or even the rewarming of geothermal well water that is injected into the earth rather than wasted on the surface. (Geologic studies of earth and rock thermal conductivity, permeability to fluid flow under various pressure conditions, and the like, lead to the conclusion that this recoverable heat is about one-fourth the total.)

But why exhaust a geothermal reservoir in a century, or in any selected time interval? Since it is replenishable by natural processes, it may be possible to enhance those processes, managing the reservoir so as to draw on it and enjoy its benefits for a longer time.

In practice, today some degree of overproduction is a necessity for several reasons. One is almost intuitively evident: A geothermal resource is truly in balance only in its unexploited state, but its natural heat dissipation is usually so low, slow, and diffuse as to be useless. To spread development and plant costs over as much power production as possible, and to do so over a normal plant economic lifespan, encourages faster heat withdrawal. All in all, the rate of geothermal extraction from any well or field, like the rate of overall geothermal energy development, is controlled by perceptions of risk (as with any new resource), by economic uncertainty, and by technological and environmental matters.

Potential generating capacity

Beyond the USGS's assessment of 8000 MWcen of near-term resources in identified western hydrothermal systems, some more specific questions need to be addressed on behalf of electric utilities. Such has been the purpose of numerous studies sponsored by EPRI, notably those of The Ben Holt Co. and Procon Inc. and of TRW, Inc., from which can be drawn several estimates of geothermal capacity seen to be technologically available, the cost ranges for successive increments, and some idea of a timetable. These estimates are a measure of the state of the geothermal art in terms meaningful to electric utilities.

- The hydrothermal resource associated with hot springs above 150°C in the western states is some 15,000 MWcen. This is about twice the USGS figure, extrapolated from it to account for resources that have not been evaluated but are indicated by the zones lying within boundaries defined by elevated spring temperature.

- The total western hydrothermal resource is still larger (by a factor of 2) at about 30,000 MWcen. This extrapolation assumes that even in the absence of hot springs, hydrothermal resources fairly consistently underlie those western lands that share a similar tectonic pattern and concentration of fault evidence, volcanic activity, and recorded earthquake epicenters.

- Some 6000 MWcen of geothermal capacity is available, most of it in a few large systems, at a capital cost of from \$600/kW to \$950/kW for both plant and reservoir development. (The figures are 1976 dollars and assume "overnight" construction.)

□ With a wide allowance (a factor of 2) for uncertainty in resource projection, another 18,000 MWcen may also be available during the twentieth century, again at from \$600/kW to \$950/kW in 1976 dollars, depending on the incentive to go after it.

In addition to the western hydrothermal resource, the Texas and Louisiana coastal geopressured region holds some 24,000 MWcen of potential capacity in hot water, plus about 10,000 MWcen-equivalent in the mechanical energy of its tremendous pressure, not to mention another 34,000 MWcen capacity represented by dissolved methane.

No cost experience

The rationale for costing available geothermal resources is complex, but among the major elements are power plant costs of from \$400/kW to \$650/kW. These figures are partly based on estimates made by EPRI and other research groups for specific sites. The spread accommodates design differences for such factors as salinity and condensing temperature and also the considerable variation in costing approach by different estimators.

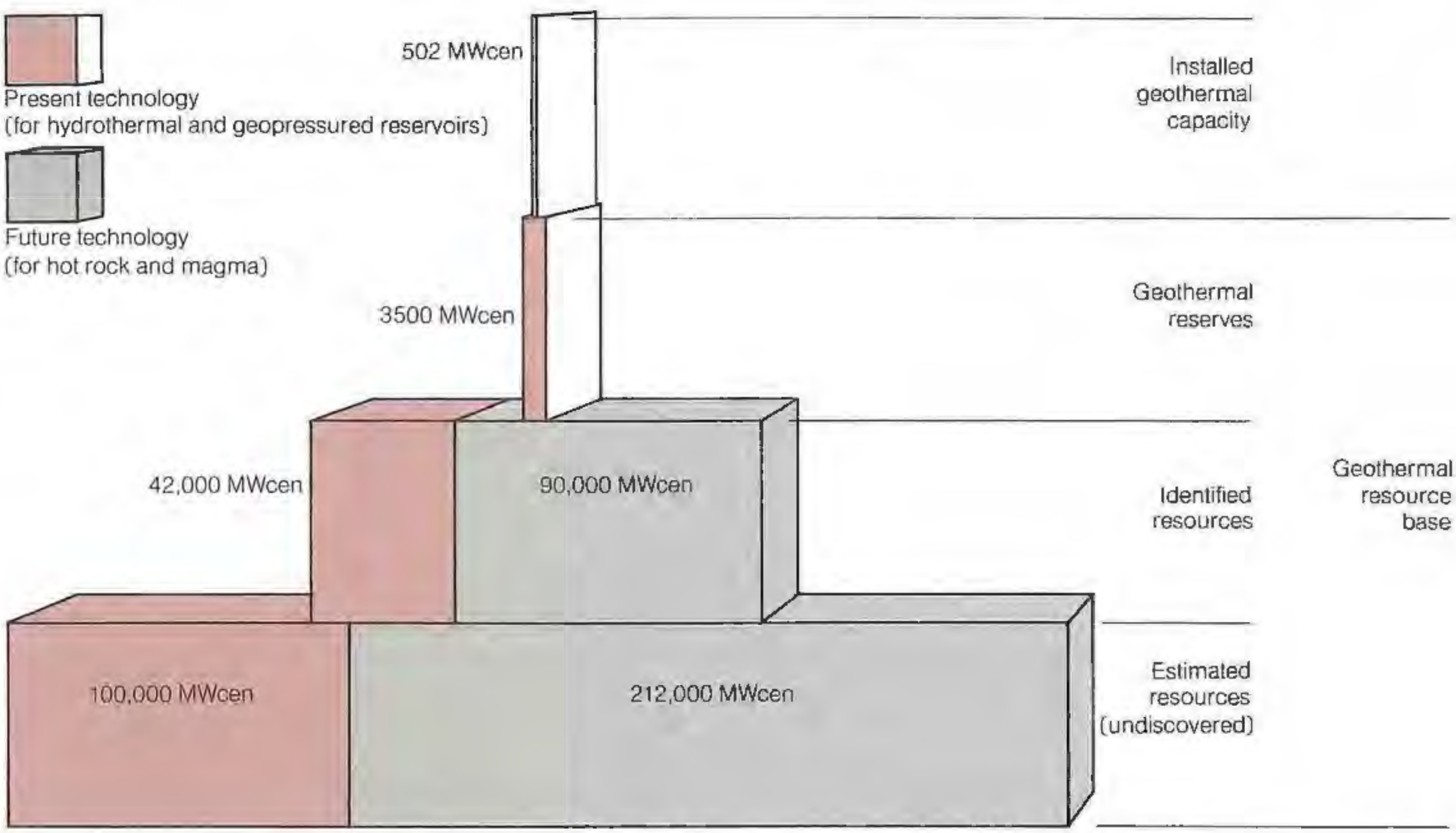
Wells are expected to cost anywhere from \$300,000 to \$600,000, depending on depth and rock type, and flow rates are taken as ranging from 200,000 to 600,000 lb/h—the lower figure being an economic minimum for any but the hottest reservoirs. Overall average cost of fluid delivered at a plant is estimated at from \$0.60 to \$1.00/10^6 Btu.

Modest improvement is forecast in technical capability to handle the high temperatures and hard volcanic rock that distinguish geothermal from oil and gas well drilling.

Resolution of these cost uncertainties for hydrothermal power generation (as opposed to steam) will come in 1980, when a 50-MW demonstration plant at Heber, California, is planned to go online for San Diego Gas & Electric Co. (SDG&E) and its utility associates.

Much of the stage for this effort was set by EPRI-sponsored research: the feasibility study, reservoir analysis (leading to the choice of Heber, just south of El Centro in the Imperial Valley), conceptual design, economic analysis, preliminary environmental assessment, and heat exchanger performance tests.

SDG&E now has three owner-



How much is down there? Today's 502-MW capacity at The Geysers is only a fraction of the potential. Expressed in electric generating capacity that would operate uninterruptedly and would last for at least 100 years, the U.S. geothermal resource base is estimated at nearly 450,000 MW. Today's technology could tap all the 146,000 MWcen hydrothermal potential (including geopressured fluids), especially the 46,000 MWcen classed as reserves and identified resources. New technology will be required to extract geothermal heat from hot rock and magma, source of the remaining 302,000 MWcen.

participants who plan to share in the project (including its output power): Southern California Edison Co., the Los Angeles Department of Water and Power, and the Imperial Irrigation District. In addition, Portland General Electric Co. and Nevada Power Co. are interested in contributing funds because of what the Heber plant can mean for geothermal development elsewhere, particularly in their own service areas. The utilities and EPRI are going ahead with a detailed design effort this year. But beyond that stage the project depends on cofunding by ERDA, which is being proposed by SDG&E.

Geothermal development pace

With electric utilities being the major present and future direct users, it follows that they are one of the three broad groups now controlling the pace of geothermal development. In turn, confidence in the resource and its economics are the main issues influencing their postures and actions. Exploration and assessment have proceeded rapidly in recent years and are now at the point where use of geothermal energy is development- rather than resource-limited. Some 100 utilities in 13 western and Gulf states have geothermal prospects for development in the near and intermediate term.

Energy firms are the second influential group in the pace of geothermal exploitation. Oil companies, in particular, have leading roles in exploration and development where their technological experience and perceptions are essential (in solving rock-drilling problems, for example). There is economic motivation, of course, as with oil and gas, and the result is a sharp and shrewd focus on the best geothermal prospects. In terms of early oil exploration, "you take the seeps first," then go on to the shallow wells in the best fields, taking what is most convenient.

Public and regulatory groups together are the third influence, motivated by the new institutional and environmental issues that surround the new energy form. Because geothermal energy is essentially untransportable, the sites of resource production and of electricity generation coincide: the power plant is not on the wellhead, but it is close at hand. The unregulated geothermal producer and the regulated electric utility must distinguish clearly their responsibilities, costs, and inevitable interactions.

These wells, operated by Union Oil Co., supply dry steam to PG&E's first two units at The Geysers, 90 miles north of San Francisco. U.S. geothermal power generation on a continuing basis began here in 1960. The tallest plume is from a well that is "on standby" and is being allowed to vent slowly to maintain a clean flow. The plume on the right is from the cooling tower for PG&E's 11-MW and 13-MW turbine generators. Steam is also emerging from fumaroles (natural vents) characteristic of the area.

Certainty for western states

In great measure geothermal energy can be exploited today; the uncertainty of the resource itself is more of a limitation than is current technology. Steady dependability of a steam or hydrothermal well and how long it will produce are the main questions. Only experience can dispel them. Systematic assessment and demonstration are preliminary steps. They have been done for dry steam and are well under way for hydrothermal energy. Today we have The Geysers. Tomorrow, the Salton Sea trough and a much wider area of the Southwest. Then, by the turn of the century, the rest of the West and the Gulf Coast states of Texas and Louisiana.

Joseph Fisher: An Energy Leader in Congress

The second-term congressman and EPRI Advisory Council member speaks his mind on the new administration and Congress and on his personal hopes for the country. ▫ An EPRI interview

Long before the Arab oil embargo dramatized the energy crisis, Joseph Fisher was guiding the efforts of various experts in determining the best ways to use and conserve the world's natural resources in his role as president of Resources for the Future, a Washington, D.C., research organization.

Fisher soon moved on and was elected to Congress in 1974 in an upset victory over an incumbent who had held the seat for 22 years. Representing northern Virginia, Joseph Fisher was one of that new breed of congressmen who believed the days of the seen-but-not-heard freshman legislator were over.

When it was decided that no amendments would be allowed on legislation revising the country's estate and gift taxes, Fisher and fellow member of the Ways and Means Committee Abner Mikva, congressman from Illinois, refused to go along. In a seldom-used move they took the matter to the full Democratic Caucus and forced a change.

Unlike many of his fellow members of Congress, Fisher is a maverick in his willingness to address long-term problems. His dream for the country is to "have a democratic, representative government that will continually address its long-term problems and opportunities, arrive at a consensus on objectives, and then proceed within its free institutions to make necessary policies and plans for realizing the goals."

As a member of the House Ways and Means Committee, Fisher was appointed to coordinate the committee's seven energy task forces and to prepare a set of energy policy proposals during the last Congress. Those proposals were watered down on the floor of the House and most of them never made it through the Senate. Fisher says bluntly that "Congress ducked the issue."

One of the problems, he says, is that jurisdiction over various energy matters is split among several committees.

"By stretching the point a bit, you could say that every committee in the House and Senate has some involvement

"I hope that with the new Congress and administration we can move the energy policies of the country toward consistency, and keep them there in the longer range."

in energy matters because energy is basic to everything," he says. He explains, however, that there are five committees, of which the House Ways and Means Committee is one, that have principal jurisdiction over energy legislation.

Fisher favors the appointment of an ad hoc select committee on energy that would basically consist of the chairmen and the leading members of those committees. This committee on energy would have authority to prepare bills and to work closely with the administration so that "everyone works toward one comprehensive energy plan that can pass Congress and also be acceptable to the president." The second-term Democrat feels the present system doesn't work very well. He says that as the system now stands, "even if the president sends Congress a comprehensive and consistent energy package, the proposals will be sorted out and considered by separate committees, such as the House Ways and Means Committee or the Science and Technology Committee."

Shortly after being interviewed in late December, Fisher was elected to the House Budget Committee. The House committee and a corresponding committee in the Senate review the federal budget as a whole, set priorities for federal expenditures, and relate these expenditures to anticipated federal revenues.

The soft-spoken congressman is very eager to participate in President Carter's plans to reorganize the federal bureaucracy. And although he warns that "the great problems of the country cannot be solved by reshuffling the boxes," he does feel that there is something to be gained "just by shaking the system."

Specifically, Fisher states that in the executive branch it would be advantageous to have one person head the two principal government energy agencies—the Energy Research and Development Administration and the Federal Energy Administration. Fisher remarks that the proposed creation of a department of energy and natural resources would also be desirable, although that might not take place for some years. In the meantime, he recommends consolidating the energy programs in government as best we can.

When can the nation expect to have a national energy policy? Three and a half years after the Arab oil embargo, with domestic oil production declining, we see oil imports growing to over 40%.

Congressman Fisher points out that at any given time there is *a set* of policies on energy, transportation, housing, and other areas. But there is never one, single policy.

"That term *a national energy policy* is passed off rather glibly," he says. "What we have are a lot of pieces, and we hope that the whole adds up to something that's consistent. I hope that with the new Congress and administration we can move the energy policies of the country toward consistency and keep them there in the longer range."

The congressman is optimistic that with new Senate and House leadership and with a new president in the White House, it's going to be different from the last Congress "when the president vetoed most of the bills that Congress sent him, while Congress, in turn, wasn't interested in the proposals of the president."

Where will the legislative emphasis be on energy? According to Fisher (who, in addition to his congressional duties, serves on the EPRI Advisory Council and was its first chairman), new measures will be brought to restrain oil imports, perhaps through a sliding tariff or quota system. In addition, he says there will be "lots of bills to stimulate energy conservation, especially in areas of home insulation and home design."

Fisher is also working on measures to increase the efficiency of new air conditioners by means of producer tax incentives or charges levied against wasteful instruments. At the same time, Fisher foresees new proposals that will encourage expanded production from existing domestic oil and natural gas reserves, including offshore drilling with tighter environmental safeguards.

The representative of Virginia's 10th Congressional District also believes that the House Ways and Means Committee

"The American people have been accustomed to cheap and plentiful energy in a variety of forms for a long time . . . the expectation has to be changed."

can and will play a very special role in new energy legislation. (The traditional jurisdiction of this committee is taxes, tariffs, and import quotas.)

"The way you try to affect the operation of a private industry is largely through taxes and tax incentives," he explains. "If you want companies to invest in exploration and the development of energy commodities faster or differently, about the best way to do it is by providing tax incentives. In the same way, if you want to get conservation moving faster than it otherwise would, be it in industry or among consumers, the best way to do it, again, is by tax incentives or some kind of stimuli."

Fisher admits that it is often difficult for legislators to balance the ticklish problem of public popularity versus the advice of technical experts on energy priorities.

He acknowledges that it is "always a tug-of-war," unless a congressman is on a committee that is deeply involved in hearings with technical experts. Other congressmen, who are not exposed to the technical experts, are more inclined to respond to popular desire. But Fisher does not believe that responding to public pressure is wrong "because decisions that don't have consensus and broad support tend not to work well."

As an example, he cites a Ways and Means Committee bill he proposed in the last Congress that would have placed a fuel efficiency tax on new automobiles, beginning with the 1978 models. It would have resulted in a progressive tax on cars getting less than 18 miles per gallon, with this figure going up slightly each year for a number of years. The bill was defeated mainly by the combined opposition of automobile companies and the unions.

Looking back, the congressman acknowledges that if "you can't get the support, you probably don't deserve to have your bill passed."

With a background in economics and a reputation as a national energy leader, Fisher feels a special responsibility to warn the public not to be taken in by their "love affair with solar energy." He does not hesitate to caution his fellow congressmen to "watch themselves and not overrespond in solar or any other new technology with more money than there are ideas or good people to develop it."

Fisher sees the enthusiasm over solar energy, for all its more distant promise, as an escape, for many people, from other problems.

"The American people have been accustomed to cheap and plentiful energy in a variety of forms for a long time. And the energy industries, including the utilities, have boasted that their performance has given the American people all the energy they want at low cost; then rather suddenly, it turns out that there isn't an endless supply of energy at low cost. So, the expectation has to be changed, although up to now the American people have not been willing to face the music."

Fisher concedes that Americans do not want to give up setting the thermostat at 75, nor do they want to give up riding in big automobiles that consume a lot of gasoline. But although they do not want to do it willingly, he does think that over time they can be persuaded to change by higher prices, by educational campaigns, by taxes, and by other incentives. "But it is not something that happens with a snap of the fingers," he says.

Although the congressman does feel that solar and other new technologies have an important place in our country's energy future, he says that conservation, coal, and nuclear power are going to have to be the immediate answer. And people are just going to have to conserve, as well as face the "dirty, mucky problems of how to use more coal without too much damage to the environment and health." He also says there is no choice but to increase our reliance on safe nuclear power.

"No matter where you get the energy, there are going to be some trade-offs," he states, citing as an example a front page story last December in the *Washington Post* on the effects of increased coal use in Wyoming. The story detailed how people in northeastern Wyoming were having second thoughts about the coal boom. From initial expectations of more jobs and economic prosperity, citizens in two Wyoming coal towns were suffering from mile-long strings of coal cars that rumbled through their towns with ever-increasing frequency. At the same time, new and unforeseen social stresses were being placed on the families because of the rapid growth.

There remains no doubt in Congressman Fisher's mind that whatever our energy future, EPRI has a major role to play. He says that government agencies will be looking to Congress, as well as to EPRI and private industry, for guidance and advice, especially in this year of government change.

"EPRI should make available the best of its thinking to the new administration," Fisher comments. "EPRI ought to respond to invitations to testify as committees of the House and Senate consider various energy bills. In addition, all EPRI's reports should be made readily available to the new people who are coming in to head the energy agencies.

"I think EPRI has quite a bit to say on the best way to distribute energy R&D money, as well as having a general appreciation of what can be done and what needs to be done," asserts Fisher.

The congressman applauds the job EPRI has accomplished so far. In fact, being one of the first members of the EPRI Advisory Council, there are few people more aware of EPRI's objectives, achievements, and problems, than Joe Fisher.

He does recognize that the Advisory Council has a "distance to go yet in feeling out how it can be most helpful to EPRI in bringing public thinking into the picture." While he admits that he is not completely satisfied with the Advisory Council's role in EPRI thus far, he is also not highly critical.

"I think that the broad social and institutional issues that the Advisory Council often brings forward are sometimes thought by EPRI and its Board of Directors to be unrealistic or missing the point. But it is just at those times that they should take stock and think again."

Fisher currently serves on the Advisory Council committee involved with national issues affecting EPRI. This committee is one of four committees in the Council; the other three examine questions on environment and ecology, power sources and uses, and communications.

The congressman is optimistic about what these recently formed committees can accomplish. His committee has recommended the establishment of a joint group comprised of members of the Board of Directors and the Advisory Council to formulate a modest program of policy-related research. Such research would enable the power industry to anticipate and prepare for the impact of national policies on electric energy supply and demand. It would also inform national decisions by pointing out, at an early date and in a credible manner, the impact of policy choices on the costs and conditions of electric power supply.

The type of policy studies envisioned would involve problems associated with the utilization of coal and nuclear resources; conflicts between energy and environmental goals; energy effects of changes in national patterns of housing and urban development and in modes of transportation; prospects for, and public acceptance of, conservation measures; changes in fiscal and monetary policies as these bear on energy; and other broad issues.

Fisher feels it's essential that the Advisory Council continue to stand outside the electric power industry and provide input to EPRI on what is happening in the economy and in the country that will affect electric energy R&D.

In the field of architecture, for example, Fisher notes that the design and construction of homes is something that the EPRI staff cannot deal with expertly, but which could be addressed by the Council. Another example would be a tax policy on investment stimulation that would impact the kinds of investments taking place in electric power development.

On a personal level, Joe Fisher is a man very much in touch with his environment. The congressman has a deep love and appreciation for nature and often relaxes by canoeing in his home state. He emphatically points out that any economic growth must be reformed and redirected along lines that will be socially and environmentally acceptable over the long run.

Joseph Fisher—congressman, trained economist, dedicated environmentalist, and energy specialist—is a futurist fighting for what he believes is best for the country and his constituents. He is basically optimistic about the future of the United States and the world and believes there is enough knowledge, technology, management, and money to make things better.

"As always," he says, "the principal obstacles are less in the nature of resources than they are in the nature of people and their institutions."

Is he optimistic enough to believe that the nature of people and their institutions can ever be changed? He says he is, although such change will not be easy.

"But one hopes that it can be done in a civilized and methodical way. And that," he states, "is the problem."

During his first two years in Congress, Joe Fisher was deeply involved in the chief issues confronting the nation in the mid-1970s. Those issues—the federal budget, inflation, unemployment, tax reform, energy, and the restoration of confidence in the federal government—are going to continue to demand the congressman's attention as he begins his second term.

Prior to his election to Congress in 1974, the long-time Democrat was president of Resources for the Future, which is a private foundation for research and education on natural resources conservation and development, environmental protection, and urban problems.

A former chairman of the EPRI Advisory Council and one of the early supporters of the EPRI concept, Fisher is also a former executive officer and senior economist on the Council of Economic Advisers, as well as an economist for the U.S. Department of State. In addition to his experience in energy and environment affairs, the congressman is a professional economist, having earned a PhD in economics from Harvard.

In Congress, Joe Fisher serves on the House Ways and Means Committee, the Subcommittee on Trade, and the Subcommittee on Unemployment Compensation. Very recently, he was elected to the House Budget Committee. The House committee and a corresponding committee in the Senate review the federal budget as a whole, set priorities for federal expenditures, and relate these to anticipated federal revenues.

Outside Congress, Fisher is moderator and board chairman of the Unitarian Universalist Association, on the board of directors for the American Forestry Association, on the board of trustees for the Joint Council on Economic Education, and a member of the American Association for the Advancement of Science, the American Society for Public Administration, and the American Economic Association.

Energy and Environment Trade-Offs

Expert opinions on approaches to energy and environment risk-benefit analysis are offered in a recently published book.

Energy and the Environment: A Risk-Benefit Approach, edited by H. Ashley, R. L. Rudman, and C. Whipple, is published by Pergamon Press, Elmsford, New York, and may be ordered through bookstores at $12.50 a copy.

Cruising along a freeway in your car, you risk 1 chance in 4000 of having a fatal accident. When you travel by commercial airliner the odds improve considerably to 1 in 100,000 (statistics based on annual death rate—average citizen). These are only a couple of the countless risks we accept, often daily, in exchange for benefits we value as members of modern society. While most of us go about our daily lives giving little or no thought to such risks, there are those who do give attention to what is known as risk-benefit analysis—a study of the advantages of technical systems and the effects they have on people and on our environment as a whole.

Discussions by prominent experts on various aspects of this relatively new subject as it relates to national decision making have been published by Pergamon Press under the title *Energy and the Environment: A Risk-Benefit Approach*. These discussions of risk-benefit analysis took place in 1974 in a series of seminars at Stanford University, cosponsored by EPRI and the Institute for Energy Studies at Stanford.

In the keynote talk of the seminar, EPRI President Chauncey Starr's topic was "General Philosophy of Risk-Benefit Analysis," or as he put it more specifically, "How does society go about deciding the major issues of balance between the advantages of large technical systems that so pervade our lives and all the other elements of social value that these systems impact?"

We can no longer use the trial-and-error approach of the past in making risk-benefit trade-off decisions. New technology advances so rapidly and is put to use so quickly throughout society that the former luxury of time in which to make adjustments is no longer available. What we need, says Starr, is "a mechanism for predicting our adjustment to the technical systems and the ways these systems will move into social use." Such a mechanism has become known in professional circles as technology assessment. There is a relatively new federal Office of Technology Assessment that advises Congress on the expected impact of new and future technologies.

No clear guidelines

Unfortunately, since society typically makes its trade-offs in an empirical, trial-and-error fashion, we have no well-defined guidelines for telling us when we've passed over the boundary from an acceptable to an unacceptable trade-off, Starr points out. So we are forced to examine past decisions, ill-defined as they are, in approaching present questions such as "How safe is safe enough?" and "How clean (environmentally) is clean enough?" Clearly, Starr notes, we do not have the resources to achieve total safety and total cleanliness and still attain the benefits of our technical systems. Thus the necessity for trade-offs.

There are voluntary and involuntary risks. A voluntary risk, for instance, would be the choice of a ski slope, the assumption being that we make our own risk evaluation. If we live in a city or large industrial center, we are exposed to such environmental conditions as traffic density, air pollution, high noise levels and the like. We have little choice in these risks, so they are involuntary.

Personal response to risk is tied to the individual's perception of it in terms of time and distance: if it's close and imminent, there is great concern; if it's remote and distant, the attitude is that "it won't happen to me." On the other hand, national response to a disaster is linked to the scope of political responsibility. A major flood or earthquake, for example, prompts a federal government response in the form of aid out of a sense of national responsibility.

If we are going to do any kind of predictive analysis of risk-benefit, we have to give quantitative measures to risk situations.

How have we historically handled risk trade-off situations in technical systems? Starr examines the data compiled on major disasters—air crashes, earthquakes, floods, tornadoes, and so on—and points out that records show a large number of events where a few people are killed and a small number of disasters where there are many fatalities.

Value of life

There has not been adequate quantification of the total social value of a human life. Some early attempts to define this value were made in terms of individual lifetime earning potential. By this measure, an infant is worth more than an old man in potential productivity. It is clear we need measures that more accurately reflect societal values.

Mining is one industry where the unions representing the workers negotiate pay scales based mainly on the degree of risk involved in the work. The degree of risk in relation to the rate of pay, in effect, is a measure of the value these workers place on their lives.

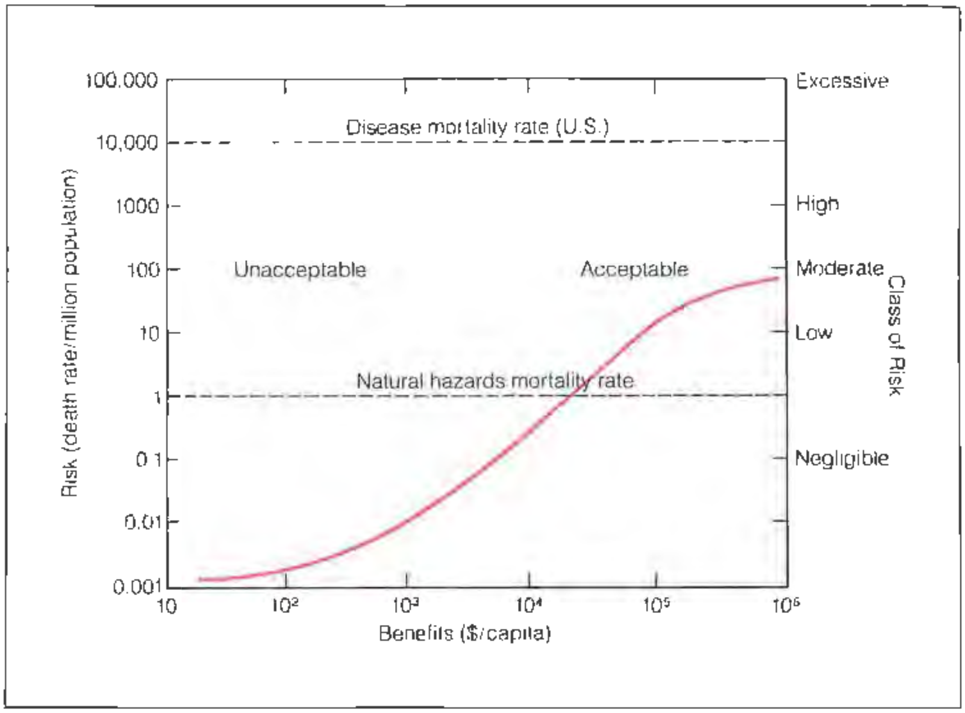
Society has made a trade-off in the death rate from automobile accidents at a level that is roughly equivalent to the death rate from disease. Having found this an acceptable level, Starr notes, "We don't really put much pressure on reducing the death rate from automobiles anymore."

An examination of accident data shows that when the individual has the choice of how to use a given system—a car or a farm tractor, for instance—the safer the system is made, the further a user will push to its safety limit. So the accident rate doesn't change much.

Voluntary and involuntary risks

Starr makes a point about the difference in the degree of safety society requires in risk exposures that are voluntary, where the individual makes the choices, and those that are involuntary, in which we usually give the government control over setting the standards. "In a society where we appoint an agency to keep us from getting hurt," says Starr, "we ask that agency to give us a thousand times more protection than if we leave it up to ourselves." He cites this example to illustrate that we require more safety in systems that others control than in those we control: Notice the distance between the knife blade and your fingers when you hold and slice a loaf of bread; then look at the distance between the blade and your fingers when you are holding and someone else is slicing.

A hypothetical relationship between involuntary risk and derived benefit is expressed by this graph. The upper and lower limits of risk are represented by the annual death rates from disease and natural hazards, respectively. Risk levels for involuntary activities are unacceptable to society if they fall above the S-shaped curve. The risk level for a 1000-MWe power plant is in the negligible range.



The historical data on death rates from accidents lead us to conclude that there is a level below which the fatality rate cannot be reduced. And that level is equivalent to the natural hazard death rate, which is 1 per million persons per year. That sets a baseline below which we can't make things safer. As an upper limit, we take the annual rate of death from disease, which is 10,000 per million. So we can set up a scale that ranges from below the baseline (negligible) to above the upper limit (excessive) as a guideline to acceptable and unacceptable risks.

What significance such a guideline would have in terms of national policy making is unclear, Starr observes, but we need such a guide "because it will tell us what the incremental effect of money spent to improve the safety of a technical system would be in terms of the choice of what system we put it into."

Future options

In a separate discussion, "Future Alternatives and Technical Options for the National Energy System," Starr lists our principal options as conservation, planning, and the traditional American way of "lucking it out."

Surveys show that residential energy use is tied to income—the higher the income the more energy consumed. High-income people use energy for amenities as well as necessities, while those with low incomes concentrate their energy use on necessities. So any reduction in energy or rise in energy price affects low-income people at the level of survival, whereas affluent people have more flexibility in cutting back. This is important to take into account, says Starr, when considering programs of energy conservation and rationing.

The long-established pattern of energy use in this country, based on the assumption of an unlimited supply of fuels, needs to be changed. The major uses of energy are in running industry (37%), powering transportation (25%), and in heating homes and offices (18%). Through more efficient use of energy in the systems we have and by way of new technology, we can effect energy conservation in industry, transportation, and in residential and office space heating. But conservation alone doesn't solve the energy problem, says Starr. "It buys us time, time to do more sensible things in terms of our energy options and social structures."

In reviewing the technical options, Starr notes that at present the utility industry relies heavily on gas and oil as fuels—gas is clean, oil is relatively clean and can be made cleaner. Recent concern over the high levels of energy imports has resulted in an incentive for industry to expand its use of domestically abundant coal. With present technology, a shift to coal from oil and gas will increase environmental costs. Utilities also favor nuclear fission—the light water reactor—since the total social costs, which eventually someone will be paying, appear to be low. Solar space heating is moderate in cost and desirable, and we anticipate developing this resource in the future. Geothermal dry steam is attractive but unfortunately is limited. Coal and uranium will be the primary sources of electricity for the balance of this century. Solar and geothermal will make only a small contribution nationally.

Let the marketplace decide

In another discussion, economist Lester B. Lave says that two of society's major decisions are answers to questions on how much electricity is to be produced and which fuels should be used. He contends that of the various ways open to us for making these decisions—by government, by experts, by the marketplace—the interplay of the marketplace is the best.

"The advantage of using the marketplace," he says, "is that if all of the costs of producing electricity—the full social costs—are embodied in the price of electricity, the market will act to produce electricity efficiently, at low cost, and in the way that the consumers desire. In the past, the full social costs have not been reflected in the price; in particular, environmental degradation was largely ignored. Past mistakes are important, but they suggest reform rather than abandoning the system."

Lave has attempted to calculate the health costs per kilowatthour of electricity produced by each of the major fuels—gas, oil, coal, uranium. Comparing coal and uranium, Lave figures that in terms of coal mine accidents, the loss of life and disability would add roughly $0.08 per thousand kilowatthours to the cost of electricity. For uranium mining accidents, the cost would be 10% as great. For chronic disease associated with mining, the costs are about three times as large as those for mine accidents. For the pressurized water reactor, public health effects are considerably less than the lung cancer risk to miners. For coal, public health effects are much greater than occupational hazards for miners; whereas for uranium, public health effects are much less than lung cancer risk to miners.

How then can we use the marketplace to decide how much electricity we should produce and with which fuel? Rather than having government, a public utility commission, or responsible business make this decision, "We would be better off by allowing the market to do it, after having the price of electricity reflect the total environmental and health costs of producing that electricity," Lave says. For the coal-produced electricity, it would mean that the price would be much higher than it was a few years ago. And for that produced by light water reactors, it would rise hardly at all, he adds.

If we used those costs, we would make sure the public had the correct information about whether or not to use electric toothbrushes and can openers, for example. We would also be giving the utilities the correct information for making decisions about what kind of and how many facilities to build. The analysis suggests, Lave concludes, "that one of the reasons for the very stringent EPA standards that came about under the Clean Air Act of 1967 and its amendments in 1969 is that there were considerable environmental costs associated with producing electricity by coal, that we were underpricing it by a factor of two, and that fact led the utilities to make a series of bad decisions."

Energy and welfare

Although they were not given at the seminar, a pair of lectures on energy and human welfare and energy and the environment by Richard J. Gonzalez, nationally recognized energy economist from Houston, are included in the book because of their particular relevance to the seminar theme. The special lectures were delivered at Stanford during the same quarter as the seminar.

In "Energy and Human Welfare," Gonzalez emphasizes the importance of "education, machines, and energy as the basis for increasing production at a faster rate than population." He says that "the potential exists for several decades during which humanity can use its intelligence and ingenuity to try to check population growth and increase production. We can change the average size of families in one generation. What it takes is education and instilling in parents a sense of responsibility for the impact of their children on their world. This is why I place such great emphasis on education."

Gonzalez lists five factors that are needed in combination, as he sees it, to bring about economic progress. The factors are knowledge, initiative, resource development, capital, and energy.

Knowledge is the basis of technology. It takes initiative and human effort to put knowledge to work to improve the world: resources must be converted into useful goods and services; capital is needed for machinery and tools; and energy is required to power the machinery, Gonzalez observes.

"The combination of these five factors in the right kind of political, social, and governmental situation determines income and wealth," he says. "And the relation, then, of those factors to population determines standards of living."

If the world is going to achieve significant economic progress, it will have to find ways of using more energy. Can we do this? There are two reasons to think we can, Gonzalez believes. First, we have used energy rather inefficiently in many cases simply because it has been cheap. And if it's no longer cheap, we clearly will use it much more efficiently. Second, there is a potential for increasing our total supply of energy.

A few ways Gonzalez cites that we can use energy more efficiently are by reducing the size and weight of our cars, upgrading our railroads, and redesigning our cities so that transportation can be more efficient—bringing closer together the places where people live and work. And we can reduce our "conspicious consumption." Gonzalez ended on the optimistic note, "I believe that we can make this a better world."

Need to balance alternatives

In his treatment of "Energy and the Environment," Gonzalez defines environment broadly, encompassing the physical world, economic life, and cultural and social institutions.

He points out that there is a great deal of pollution that occurs naturally in the world—floods and rains cause erosion, volcanic eruptions spew gases and dust into the atmosphere, sulfur oxides are naturally emitted from the earth.

As we increased our industrialization and concentrated in large cities, we became more conscious of the impact of indirect social costs, especially when it was apparent that the quality of air, for instance, had deteriorated significantly.

Gonzalez notes that at the beginning of the decade we committed ourselves to a new program—not knowing what it was going to cost or what it was going to accomplish—when we passed the National Environment Policy Act in 1970. "We literally wrote a blank check and said to the bureaucrats, 'Set whatever standards you want, just clean up the environment, don't worry about the costs,'" he says. In the case of electric utilities, he points out, "We have insisted that they use fuels with lower sulfur content. Therefore, we must pay higher rates because the low-sulfur fuels are much more expensive than high-sulfur fuels."

We have to keep in mind the need for limiting costs of environmental cleanup to keep them consistent with the total objectives we have of reducing poverty, improving education, making our cities more livable. The billions of dollars spent for environmental improvement have resulted in reducing the amount of capital available to expand plant capacity, thus limiting the growth of output in some cases, Gonzalez says.

What we have to look for is a balance of the best available alternatives that will serve our needs. Practically everything we do involves pluses and minuses, tradeoffs. We have to concentrate on what we can do for the foreseeable future by the actions we take now.

Among the things we need to give attention to is bringing population growth under control sometime early in the next century; finding ways to use renewable forms of energy; conservation and more efficient use of energy; changes in lifestyle, whereby we influence where people live and change the concentration of people in cities. Such changes won't come rapidly. We need to decide on a long-range policy and stick with it. Whether we will choose this course remains to be seen, Gonzalez concludes, with guarded optimism.

Other discussion topics

Other detailed discussions from the seminar included in the book are "Public Health Aspects of Energy Systems" by Dr. Leonard Sagan, associate director, Department of Environmental Medicine, Palo Alto Medical Clinic; "The Rate of Discount of Long-Term Public Investment," Kenneth J. Arrow, Nobel prize-winning economist from Harvard University; "Risk-Benefit Trade-Offs in Nuclear Power Generation," Wolf Häfele, director of the International Institute for Applied Systems Analysis in Laxenburg, Vienna; "Options for the Conversion of Fossil Fuels," E. J. Gornowski, executive vice president, Exxon Research and Engineering Co.; "U.S. Options for a Transition from Oil and Gas to Synthetic Fuels," Alan S. Manne, political economist with the John F. Kennedy School of Government, Harvard (now on the faculty of Stanford University); "Fault-Tree Analysis as an Example of Risk Methodology," Gerald J. Lieberman, professor of Operations Research and Statistics, Stanford University.

Coal Conversion—A Partial Answer

by George R. Hill

Given the need to switch to coal, converting it to liquid and gaseous fuels can lessen the disruption of facilities built to burn oil and natural gas.

Storm warnings went up for all to see in 1973 when the Mideast oil embargo cut a major supply and hiked the price of a basic energy source we had long taken for granted. But with the end of the embargo came a disregard of the warnings and a return to business as usual. Today the United States relies on imports for over 40% of its oil, more than before the embargo and about one-third of it still from uncertain Mideast sources.

As the energy appetite of the U.S. continues to increase, along with the rising energy needs of the rest of the world, it is crucial that we prepare now to meet the energy demands of the future. Conversion of coal to oil and gas could provide the answer and eventually free us from dependence on the Organization of Petroleum Exporting Countries (OPEC). But unless we move quickly to develop the required coal conversion technology so that commercial plants can be built with confidence, we may see a period of severe fuel shortage with consequent major economic and sociological disruptions.

It is not enough that we merely switch to coal from oil and natural gas, as has been advocated. We need to convert much of that coal, by liquefaction and gasification, to synthetic oil and gas for continued use in those forms.

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Pushing forward is essential, for even with the research and development efforts invested in coal conversion so far, it will likely be 10 years before commercial plants are tested. Experience has shown that market penetration of new technologies is sometimes slow. For instance, it has taken 30 years for nuclear-generated electric power to achieve just a 10% share of the total electricity produced in the U.S. Environmental standards, federal licensing regulations, and shortage of capital are among the factors that have delayed and continue to slow the development of nuclear power, and they can be expected to retard the advancement of new technologies for coal conversion.

Coal conversion promising

The conversion potential of coal is indeed promising. Methane, which constitutes over 90% of natural gas, can be derived from coal. Processes are available for producing supplemental natural gas from coal at a price per million Btu that is not much above that of imported liquefied natural gas. And research now under way shows promise of reducing the cost of this coal-derived natural gas by as much as 20% below the cost from present technology.

By subjecting coal to high temperatures in a hydrogen atmosphere, a petroleum-like substance can be produced that is convertible into gasoline, diesel fuel, and heating oil for use in generating electric power. The energy consumed in the conversion process is from 20% to 35% of the energy present in the feedstock. There are perhaps half-a-dozen processes that have reached the pilot plant stage for producing petroleum substitutes from coal, but no commercial plants have yet been built. Cost estimates for such commercial-size plants are placed at $1 billion, similar to that of a petroleum refinery. If we are willing to pay the price required for coal conversion, there need be no future shortage of gaseous or liquid fuels.

Fuel consumption pattern

How did we arrive at our fuel shortage predicament? Historically, the energy consumption pattern in the U.S. was based on the belief that there was an unlimited supply of fuels. The use of natural gas, petroleum, coal, and uranium increased as the gross national product grew. In recent years, however, the gas and petroleum industries have been unable to meet the increasing demand at attractive prices.

Economical domestic supplies of natural gas and petroleum have fallen short of demand. Among the results have been the denial of natural gas to new homeowners in many parts of the country, the phasing out of industrial interruptible contracts, and an alarming increase in oil imports. Before the 1950s, the U.S. supplied its entire oil needs and had a surplus for export. Just prior to the embargo, imported oil accounted for about 30% of our total supply. Now, as mentioned earlier, that figure has risen to over 40%.

The criterion "best use of fuel resources" is new for this country, forced by the fuel shortage. Natural gas, the cleanest, most versatile primary fuel, was used in many plants that could have used other fuels, such as coal or residual oil. There was a reason for this. Distributors of natural gas could justify installation of major pipelines and distribution systems only if a large market existed. By stimulating large contracts with industrial users and electric power companies, the natural gas producers established a substantial baseload, which then made it possible for them to sell gas to individual homeowners and to set up a pipeline system to supply it. Then the FPC, under direction of Congress, froze the price of natural gas at an arbitrarily low level to protect the interests of residential users. As a consequence of the low price and extensive pipeline supply network, natural gas was put to even wider use as a fuel in systems where coal and residual oil could have served.

Another major factor that has contributed to our fuel shortage is America's love affair with the automobile. The living pattern of Americans has been profoundly influenced by the automobile. The splendid network of highways and secondary roads that link the country resulted from a seemingly unlimited flow of cheap gasoline and diesel fuel for an abundance of mass-produced cars and trucks. But in recent years it became necessary for gasoline producers to reach overseas for petroleum in order to supply the enormous volumes of fuel needed to power our four-wheeled addiction. This dependency on foreign oil made us vulnerable to the contingencies of the import market, as was dramatically underscored by the embargo. A positive effect of the embargo, which could eventually lead to breaking our preoccupation with the automobile, is the attention now placed on the need for efficient mass transit systems throughout the country.

Coal has had a checkered history, waxing and waning in popularity. In the early decades of this century, coal consumption in the U.S. reached a high level as it replaced wood as the primary source of heat and energy. Then along came petroleum and natural gas to displace coal as the main fuel for space heating and for powering the railroads. Many electric utilities also turned from coal to oil and gas. Since the beginning of this century, annual coal production has been on a plateau because the expansion of utility networks increased the amount of coal used by electric utilities and thereby offset the decreased use by railroads and other consumers. However, the percentage contribution of coal as a primary energy source in the U.S. has steadily decreased.

Coal consumption in the U.S. in 1975 was 624 million tons, of which 406 million tons (65%) were used by electric utilities. The FEA forecasts an increase in U.S. coal consumption to nearly 800 million tons in 1980, over 1 billion tons in 1985, and more than 1.3 billion tons in 1990. Fortunately, the coal reserve is large —about 90% of the country's total fossil fuel reserve.

Fossil fuels a stopgap

It is evident to those familiar with the world's energy problem that fossil fuels offer, at best, a bridge to such long-range solutions as solar energy, nuclear fusion, and the use of waste, wind, and waves. Research and development work on all these potential energy sources must proceed as rapidly as can be justified economically.

The breeder reactor offers a prospective intermediate solution to meeting our electric power needs. Conversion of nonfissionable uranium-238 and thorium in a properly designed nuclear reactor can increase our supplies of fuel for electric power generation by a factor of 100 or more. However, the costs of producing electricity from a breeder reactor, as well as from fusion and solar energy, will probably be higher than from present technology. But as the past has shown, by the time new technologies are perfected the public has been able to afford them. Adjustments in energy use patterns will be made to accommodate the price.

The problem is how to best use the fuels and technology we have to generate the energy we need until the promising new technologies are developed and put to widespread use. Several steps should be taken. For instance, we ought to free the natural gas now being used on an interruptible basis and divert it to committed use in residential heating and in special industrial applications that require a clean fuel. The use of clean fuels should be restricted mainly to those applications where substitutes are not possible.

We need to pursue discovery and development of new natural gas and oil reservoirs. We should move forward with production of fuels of required purity from coal, oil shale, tar sands, and by secondary and tertiary recovery methods from petroleum. Research and development in improving the state of the art of energy conversion must be continued. The relative costs of producing energy by new methods need to be calculated and taken into account as the new technologies become economically viable.

At the same time, we must increase our efforts to achieve energy conservation through such methods as insulating homes and designing new homes, commercial buildings, and factories to make use of sunlight as an energy source. City and industrial planners need to bear in mind the desirability of siting plants and housing at convenient distances from each other. Mass transit systems need to be planned and built for the efficient, convenient movement of people and to reduce automobile use.

The current slowdown in construction of electric power plants resulting from the recession and the accompanying decrease in electricity demand will have to be reversed if the projected future power demands are to be met. Most utilities anticipate building a number of oil-fired plants to take up the slack in supply. This type of plant is quicker and less expensive to build than coal-fired plants, which need more complicated materials-handling facilities and require stack-gas cleanup systems, or their equivalent, to meet federal clean air standards. As soon as utilities can get supplies of coal that meet these standards, they plan to construct major coal-fired power plants.

If the utility companies could be assured a continuing supply of oil for turbine-powered generating plants and for direct firing of boilers, they would no doubt maintain existing plants and in addition, plan to build less costly oil-fired facilities. Eventually, oil from petroleum will become scarcer and too expensive unless supplemental sources are available. The two such sources that have potential for conversion development within the next 10 years to supply required needs are coal and oil shale. The cost of oil from either of these sources will probably be higher than current prices for imported oil. The major U.S. oil companies are reluctant to build commercial-size conversion plants because of the uncertainty that the end product can be sold at a profit. For instance, OPEC producers could drop the price of their oil sufficiently to make the synthetic fuels from conversion unmarketable. So it is unlikely that U.S. companies will venture into the coal and shale oil conversion business without some form of risk protection and price guarantee. Financing of conversion plants with a guaranteed return on investment is needed in order to move forward with the essential work of proving at least one production process for coal liquefaction and one for shale oil.

From R&D to commercialization

The programs supported by ERDA aimed at improving the processes for energy production need to be continued for they lead to lower-cost second-generation plants. However, in order for the new technologies to reach the commercial market, companies with the capability of commercialization must be involved early enough so their staffs can acquire the skills and technical know-how required. The technology-transfer problem demands that personnel familiar with production and plant operation be factored in soon enough to ensure that the commercial unit is put on stream by a target date.

Currently, much government-supported research is conducted in discontinuous stages. Research is done by one group, extending through the process development stage. Those involved in the research and development phase ordinarily do not also build and operate the pilot plant, since each phase of the work is treated as a separate package. Entirely different groups frequently are involved in constructing the demonstration plants.

Theoretically, after the demonstration plant stage, any company could build a commercial plant with the knowledge then available. But historically, no group has stepped forward to build a plant developed with government funding because it is common knowledge that initial commercial-size units rarely are as economical as the second and third units that would later be built by a competitor. The only exceptions have been nuclear power and space technology development, including the moon shuttle, where government laboratories played a principal role because no counterpart technology existed in private industry. The national laboratories and contracting industrial groups provided a combination that brought these enterprises to fruition within the normal economic pattern of the country.

However, in the case of energy development—electricity and liquid and gaseous fuels—there already exists an economic system that is an integral part of the national structure. Plans and processes developed in national laboratories rarely are transferred to the private sector unless the development work is done by the companies that subsequently build the commercial plants.

Need to revise approach

In some instances, development of the required technology has taken a different course. At the start of World War II, there was a critical need for synthetic rubber and for high-octane fuels for military aircraft. The processes in each case were developed by awarding contracts to companies with the necessary technical capability and experience in related areas to build large plants. The front-end capital was provided by the government. After the plants were in operation and proved economically viable, they were sold on a bid basis either to the companies that had developed them or to their competitors.

It is recommended that a similar procedure be followed for development of first-of-a-kind plants for producing oil from coal and shale, high-Btu gas from coal, and electricity using fluidized-bed combustion. The company given responsibility for each program would understand that the plant design and all requisite know-how would be available to any company desiring to build such a plant. If economic conditions were such that the plant could operate at a profit, it could be sold for the cost of construction to a company that would operate it as a commercial enterprise. And should the price of the resultant product prove competitive with available petroleum supplies, revenue from the sale of the oil would be plowed back to pay for the plant.

The important accomplishment here would be that problems always present in first-generation plants would be solved in the construction and shakedown stages, and we would have a viable, proven technology for production of supplemental fuels.

We would get the same results if one commercial plant of each type we've mentioned was built. Currently, there is no knowledge of the real cost of using the new technologies to produce oil or high-Btu gas or electric power.

Successful operation of the first one-of-a-kind plant is imperative if we are to place a ceiling on the price of imported oil. We could then avoid serious economic dislocation during the 20-year transition period to advanced technologies. Since we have a plentiful domestic coal supply, the cost of this raw material for the conversion plant would remain stable. As the price of OPEC oil escalates, it would reach the point of parity with the demonstrated cost of oil from coal and shale. Petroleum companies would then be willing to invest stockholder capital in building new plants, since there would be assurance of a fair return on investment.

The U.S. is facing a critical period in its economic history. Solutions to the problems are available by using methods applied successfully in the past. It is earnestly hoped that the necessary programs will be implemented before the situation becomes more critical.

At the Institute

Board Increases Funding for Coal Liquefaction Pilot Plant

EPRI's Board of Directors increased to $40 million EPRI's share in a joint government-industry effort to design, construct, and operate a 250-ton/day pilot plant for demonstrating a process to derive clean liquid power plant fuels from coal.

Wagner Warren Scullthorp Esswein

At a February 4 meeting in Atlanta, Georgia, the Board authorized nearly $64 million for electric energy research involving 45 new projects and 23 ongoing projects. The $40 million will go toward demonstration of the Exxon Donor Solvent process, a method of coal liquefaction that is at a relatively advanced stage of development and appears to compare favorably with other candidate processes.

In fossil fuel research, the Board approved two new projects geared toward helping the industry meet air quality standards for coal-burning power plants. In one, EPRI will provide funds, subject to further approval by the EPRI Research Advisory Committee, for additional testing and evaluation at an advanced coal-cleaning plant being built by General Public Utilities at Homer City, Pennsylvania. The plant would provide a cost-effective method for cleaning ash and sulfur from coal before combustion. The second project is for the design, construction, and operation of a 10-MW test facility for developing advanced sulfur oxide scrubber systems.

The Board also approved an important ecological study to assess the differences among fish species in their tolerance toward heated water discharged from power plants. In the area of energy supply, another major study will investigate the geochemistry of uranium deposits to improve the ability to predict the location of such deposits.

A number of projects were also approved in the area of electrical systems research for increasing the reliability of electric energy transfer. In nuclear power research, several projects were authorized on improving nuclear power plant safety and availability.

Another major action of the Board resulted in the election of Aubrey J. Wagner to the Executive Committee of EPRI's Board of Directors. Wagner, who recently became a director of EPRI, is now serving his second term as director and chairman of the Tennessee Valley Authority. He has also served as a member of several presidential councils and commissions. In addition, the Board elected as its vice chairman Frank M. Warren, president of the Portland General Electric Co.

New members were appointed to EPRI's Advisory Council and Research Advisory Committee. Appointed to the Advisory Council was Lenton G. Scullthorp, vice chairman of the Michigan Public Service Commission. The Advisory Council provides liaison between the public and EPRI's Board of Directors, officers, and staff.

The new member of the Research Advisory Committee is L. A. Esswein, manager of corporate planning for Union Electric Co. in St. Louis, Missouri. The Research Advisory Committee advises EPRI by helping to identify and rank R&D needs of the electric utility industry.

At the present time, EPRI is managing or has completed more than 900 projects under contract to manufacturers, universities, research institutes, and other organizations. The value of these projects, including funding from cosponsors, is almost $752 million; EPRI's share is $569 million.

Major Support for Zinc-Chlorine Battery

Key participants in a recent press conference to announce further development of the zinc-chlorine battery for energy storage display the frozen chlorine hydrate: (from left) Philip Symons, chief scientist, Energy Development Associates; Robert Loftness, director of EPRI's Washington, D.C., office; Art Guffey, executive vice president, Hooker Chemical Corp.; and Milton Hollander, vice president of technology, Gulf and Western Industries. Also participating in the press conference were two utility executives: Sidney H. Law, director of research and system studies for Northeast Utilities Service Co., and Peter A. Lewis, assistant manager for research and development, Public Service Electric and Gas Co.

A $3.8 million award was recently given by EPRI to Energy Development Associates (EDA) for the continued development of the zinc-chlorine battery. EDA is matching the award with equal funding for a total of $7.6 million.

"This award represents a major step forward in our program to develop an advanced energy storage battery for utility use," stated Dr. Robert Loftness, director of EPRI's Washington, D.C., office at a New York press conference, where the new award was first announced.

The 39-month effort will lead to the fabrication and testing of a 10-MWh prototype zinc-chlorine battery. Currently the only practical technology for storing energy is pumped storage. Researchers have been working on other kinds of advanced storage batteries that employ sodium-sulfur and lithium–metal sulfide, but EDA and EPRI officials believe that the zinc-chlorine version is the furthest along.

The present program calls for investigators to design, fabricate, test, and evaluate a 100-kWh battery submodule in 1977. The effort will then involve research, development, and engineering leading toward construction of two 1-MWh battery modules in 1978 and a 10-MWh battery system by 1980. The 1-MWh battery module is the basic building block for utility use. Commercially, about 100 of these modules might be sited at a distribution substation in the utility network. The resulting 100-MWh system could level the load for a utility system serving the needs of a town of 60,000 people.

The battery harnesses the chemical energy released by the reaction of zinc and chlorine in the formation of zinc-chloride. According to Milton Hollander, a director of EDA, the major innovation in EDA's research was learning how to store chlorine (which by itself is volatile and poisonous) as a solid yellow chlorine hydrate. The battery's advantages, according to Jim Birk, EPRI project manager for battery development, are that it operates near ambient temperatures and uses a water-based electrolyte. All the other advanced energy storage batteries operate at much higher temperatures and use either molten salt or ceramic electrolytes.

The capital cost goal of the fully developed zinc-chlorine battery is $25/kWh, the same cost as a pumped hydro storage system.

It is anticipated that the 10-MWh system will be the first advanced battery to be tested in the national Battery Energy Storage Test (BEST) Facility, which is scheduled for completion by 1979. The BEST Facility is now being designed and will be constructed by Public Service Electric and Gas Co. of New Jersey on a PSE&G substation in Hillsborough Township, Somerset County. The jointly funded EPRI–ERDA project will test prototype batteries under closely controlled conditions.

Economics Analyses Presented

Project Manager James Savitt of Wharton Econometric Forecasting Associates presents the results from an EPRI project to a December seminar at the University of California at Berkeley. The Wharton project is geared to analyzing and forecasting energy use for transportation services. Results from a companion project with Math Tech, Inc., on the implications of electric automobiles on utility systems were discussed by Pat Marfisi.

Energy-Economy Modeling Workshop

On January 4 and 5 a workshop was held at EPRI headquarters to develop energy-economy scenarios that could be run on the Wharton Annual Energy Model.

Ideas for scenarios were suggested by W. Thompson, Philadelphia Electric Co.; D. Walters and B. McPhee, TVA; R. Weber, Public Service Electric and Gas Co.; N. Ricci, Wisconsin Electric Power Co.; and other participants from EPRI and the academic community.

Among the questions posed for possible analysis were: What would be the effect of continued energy shortages on unemployment and inflation? What would be the effect on the national economy of another energy supply interruption, such as the Arab oil embargo? What would be the best response by the U.S. government to another embargo? How rapidly will the demand for electricity grow under varying assumptions about future national income?

A January 4 and 5 workshop at EPRI examined the effects of energy costs and availability on the national economy. Discussing the proceedings are (from left) Bill Finan of Wharton EFA; Lawrence Klein, president of Wharton; and Stephen Peck and Martin Greenberger of EPRI's Systems Program.

The Wharton Annual Energy Model was designed under an EPRI research project that examined the effects of energy cost and availability on the national economy. The Annual Energy Model was developed from the Wharton Annual Industry Model, which has provided commercial forecasts for some years. It was built under the guidance of L. R. Klein, a professor at the University of Pennsylvania and a pioneer in the field of macroeconometric modeling.

The workshop included a discussion of recent progress on the Annual Energy Model and a consideration of ways to model supply constraints.

Turbine Workshop

John Mundis, EPRI Nuclear Engineering and Operations Department, confers with Ralph Ortolano, senior apparatus engineer, Southern California Edison Co., and Paul Lewis, manager of engineering for R&D, Mechanical Technology, Inc., at a recent three-day workshop on improved turbine availability. About 70 people attended the workshop, which was sponsored by EPRI's Nuclear Engineering and Operations Department, Nuclear Systems and Materials Department, and Fossil Fuel Power Plants Department. The workshop was held in cooperation with the EEI Prime Movers Committee, Steam and Combustion Turbine Subcommittee.

Power Cable Test Facility

A test facility in Waltz Mill, Pennsylvania, will someday affect the lives of millions of Americans, although the effect will never be seen, and that is the whole purpose of the Waltz Mill Underground Cable Test Facility. It is here that tests are made daily on underground power cables—an increasingly important alternative to overhead transmission lines in areas that are either densely populated or have environmental constraints.

Supported by the electric utility industry since 1967, the facility is owned and operated by Westinghouse Electric Corp. An agreement signed in early February, however, will result in EPRI's being responsible for the facility's operation as of June 15, 1977.

In fact, two agreements were signed by EPRI and Westinghouse. The first calls for EPRI to lease the facility from Westinghouse at a cost of $7 million for a period of 10 years. The second contract makes Westinghouse the operator of the facility on behalf of EPRI for the first 3 years of the lease.

Essentially, the agreements allow EPRI to have managerial control over the research program and to make capital improvements.

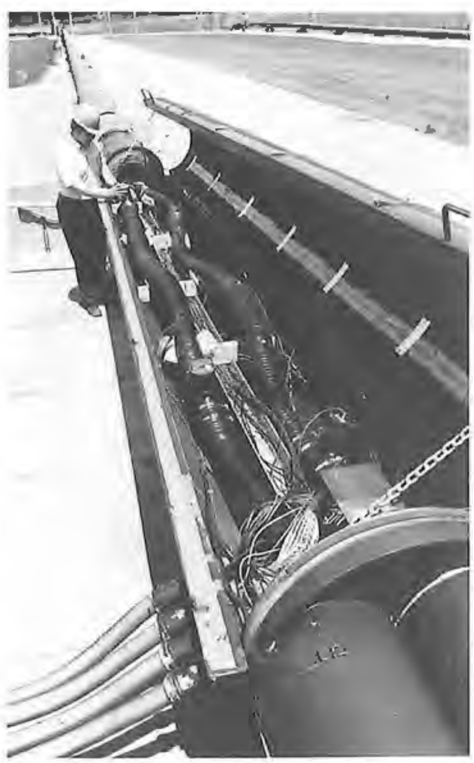
At Waltz Mill, new cable designs are installed and operated under realistic field conditions. Such tests are usually carried out during a two-year period in which the cable system is regularly overloaded and subjected to overvoltages.

"If a cable system survives this test satisfactorily, it can normally be said that the cable is good for a 20- to 40-year actual service life," says John Dougherty, director of EPRI's Electrical Systems Division. Dougherty explains that it is less expensive to pinpoint any shortcomings in a new cable during the Waltz Mill phase than after the cable has been bought and installed by a utility.

Proving out different cable designs and technologies at Waltz Mill is an integral part of EPRI's objectives in underground transmission development, which are to provide reliable cables with higher voltages and capacities.

Underground lines cost five to twenty times more to install than overhead lines. EPRI officials believe that more and more underground transmission and distribution lines will be installed as costs are brought down, although it is unlikely that it will ever pay to put all lines underground.

Under the terms of two contracts signed early in February by EPRI and Westinghouse Electric Corp., EPRI is responsible for the operation of the underground cable test facility at Waltz Mill, Pennsylvania, and Westinghouse will operate the facility for EPRI. Signing the agreements are (seated, from left) Chauncey Starr, president of EPRI, and Herbert Gray, vice president, southeastern region, Westinghouse; (standing, from left) Joe Dillard, manager of the Advanced Systems Technology Division, Westinghouse; Charles Paine, manager, southeastern zone, Westinghouse; and John Dougherty, director, EPRI Electrical Systems Division.



A typical test inspection port showing a solid dielectric cable splice under evaluation at Waltz Mill.

Project Highlights

EPRI Negotiates 30 Contracts

Number	Title	Duration	Funding ($000)	Contractor / EPRI Project Manager
Fossil Fuel and Advanced Systems Division				
RP239-4	Economic Studies of Alternative Coal Gasification	18 months	500.0	Fluor Engineers and Constructors, Inc. *M. J. Gluckman*
RP642-1	Open-Cycle MHD Generator Inverter Interaction Test	1 year	248.3	Avco Everett Research Laboratory, Inc. *P. S. Zygielbaum*
RP779-11	Testing of Paraho Shale Oil	2 months	8.0	Paraho Development Corp. *R. Wolk*
RP780-2	Emission Analysis Services	1 year	73.4	LFE Environmental Analysis Laboratories *R. Carr*
RP780-3	Emission Analysis Services	1 year	74.7	Meteorology Services, Inc. *R. Carr*
RP786-1	By-product–Waste Disposal for Flue Gas Cleaning Processes	1 year	198.0	Michael Baker, Jr., Inc. *T. Morasky*
RP787-2	Capital Costs of Advanced Batteries for Utility Energy Storage	1 year	55.0	Arthur D. Little, Inc. *J. R. Birk*
RP832-2	Evaluation of Advanced Liquefaction Concepts	8 months	93.4	Catalytica, Inc. *H. Lebowitz*
RP834-1	Economic Evaluation of Fabric Filtration Versus Electrostatic Precipitation for Ultrahigh Particulate Collection Efficiency	11 months	150.0	Stearns-Rogers, Inc. *D. Teixeira*
RP905-1	Acceptance Test Methodology for Cooling Towers	10 months	21.6	Environmental Systems Corp. *J. S. Maulbetsch*
RP910-1	Trace Element Removal by Absorption on Iron Hydroxides	2 years	149.9	Stanford University *R. Jordan*
RP914-1	Fixed-Bed Gasification–Combined-Cycle Control Study	2 years	785.0	General Electric Co. *M. Gluckman*
RP924-1	Phoenix House Solar-Assisted Heat Pump System Evaluation	4 months	45.0	Kaman Sciences Corp. *J. E. Cummings*
RP927-1	Waste Heat Rejection From Geothermal Power Plants	10 months	149.3	R. W. Beck & Associates *P. LeMon*
RP982-1	Development of a Process Design/Evaluation Data Book for Lime-based FGD Systems	1 year	85.5	Pedco-Environmental Specialist, Inc. *T. M. Morasky*
Nuclear Power Division				
RP248-2	EFLOD Code Development for Reflood Heat Transfer	9 months	'6.2	University of Texas at Austin *L. Agee*
RP891-1	On-Line Analysis of Power Plant Disturbances	6 months	177.4	Systems Control, Inc. *A. Long*
RP891-2	On-Line Analysis of Power Plant Disturbances	42 months	189.9	Combustion Engineering, Inc. *A. Long*
RP892-5	Acoustical Imaging of SS Samples	4 months	4.8	Lockheed Missiles and Space Co., Inc. *E. Reinhart*
RP895-1	Power Shape Monitoring System	3 months	50.0	Exxon Nuclear Corp. *F. E. Gelhaus*
Electrical Systems Division				
RP213-3	Fault Data Acquisition System and Data Logger for the HVDC Compact Terminal	25 months	559.9	Boeing Engineering and Construction *S. Nilsson*
RP764-2	Research in Long-Term Power System Dynamics	26 months	366.5	General Electric Co. *P. M. Anderson*
RP796-1	Composite Wood Utility Poles	3 years	366.0	Michigan Technological University *R. S. Tackaberry*
RP930-1	Gas-Insulated, Vaporization-cooled Transformers	25 months	1050.0	Westinghouse Electric Corp. *R. Tackaberry*
Energy Analysis and Environment Division				
RP664-2	Critical Assessment and Modification of the Bechtel Energy Supply Planning Model	7 months	15.0	Dr. J. Daniel Khazzoom *R. Michelson*
RP676-2	Laser-induced Fluorescence to Study Power Plant Plume Chemistry	3 months	2.4	Georgia Tech Research Institute *C. Hakkarinen*
RP855-1	Characterization of the Ecological Effects of Overhead Transmission Line Rights-of-Way	21 months	199.5	Asplundh Environmental Services *K. Ray*
RP879-1	Evaluation of Chlorine Monitoring Techniques	1 year	93.6	Public Service Electric and Gas Co. *R.K. Kawaratani*
RP880-1	Synthesis and Analysis of Cooling Impoundment Information	18 months	143.8	Battelle, Pacific Northwest Laboratories *R. A. Goldstein*
RP939-1	Aquatic Microbiomes for Assessment of Effluent Effects	1 month	55.8	Lawrence Berkeley Laboratory *R. K. Kawaratani*

Earthquake Effects on Nuclear Power Plants

EPRI is investigating the response of model nuclear power plant structures to simulated earthquake ground motions through a contract recently awarded to the Civil Engineering Research Facility at the University of New Mexico.

The project is part of a program on the interaction of soil and nuclear power plant structures. Investigators are studying how a seismic event might be transmitted through soil to a nuclear plant. The purpose of the program is to provide an expanded data base and new methodologies that will allow for more efficient designs of nuclear power plants.

"Nuclear plants are designed according to very strict and conservative standards to withstand the effects of a hypothetical seismic event," stated Conway Chan, EPRI program manager for the research effort. "The current study will expand our knowledge in this area and provide us with new options for evaluating possible earthquake effects."

The overall program involves the development of methods for generating earthquakelike ground motions with conventional high explosives; a series of studies with soil response models; the testing of scaling laws to permit investigators to use small models in lieu of an actual full-scale experiment; and the testing, which will begin shortly.

During the testing at a site south of Albuquerque, strong earth-shaking will be induced by conventional explosives; both the ground and the models will be heavily instrumented to measure the response to the movement. Of the five models to be used in the test, the largest will be 12 ft (3.66 m) in diameter and 5 ft (1.52 m) high. The smallest will be 3 ft (0.91 m) in diameter and 3.75 ft (1.14 m) high. One of the models will be buried underground.

Data Lacking on Health Effects of Sulfur Oxides

Information is badly needed on the health effects of various sulfur oxides that people may be exposed to from the burning of fossil fuels. Until this information is available, it's difficult to make rational decisions for setting sulfur emission standards and for developing emission control strategies.

These were the conclusions of a study recently released by EPRI, which is based on a one-year evaluation of current data and information. The EPRI-sponsored study was conducted by the San Rafael, California, research firm of Greenfield, Attaway & Tyler, Inc.

Electric utilities are particularly interested in this issue because they are the major users of the nation's coal. The issue is timely because emission standards on sulfur oxides will be reviewed by the government in the near future.

Efforts are also needed on the development of technologies for controlling sulfur emissions from fossil fuel combustion. The type of control system and the costs of its operation will depend on the amount of emission reduction necessary. Because coal use is expected to increase dramatically in the years ahead, research on sulfur oxides has a special urgency.

"Utilities must protect public health but must also avoid pollutant controls that raise electricity costs without providing significant environmental and health benefits," says Dr. Cyril Comar, director of EPRI's Environmental Assessment Department. The cost of sulfur controls can run into billions of dollars.

"The report makes clear just how complex the issue really is," states Dr. Comar.

Although sulfur dioxide is the main sulfur compound emitted into the air, the report notes that this substance has been thoroughly studied by scientists and by itself appears to pose no threat at present levels.

Instead, the report says, other sulfur compounds, such as sulfates, sulfites, or sulfurous and sulfuric acids, may be more important to study than sulfur dioxide—especially because these compounds may combine in the air and act together with such pollutants as particulates, nitrogen oxides, photochemical oxidants, and polycyclic organics.

The report, *Sulfur Oxides: Current Status of Knowledge*, EA-316, concludes by describing the type of research needed. In particular, it urges researchers to investigate which sulfur compounds pose health threats, under what circumstances, and how these compounds react with other air pollutants.

Safer Power Transformers

EPRI has announced a new research project to develop safer power transformers.

The objective of the $2 million study is to develop gas-insulated, vapor-cooled transformers that compare economically with oil-filled units but eliminate the fire hazards sometimes associated with oil. In addition, the project will provide a substitute for polychlorinated biphenol—a compound that has been widely used in transformers but is now banned because of its nonbiodegradable characteristics.

It is anticipated that the two-year project will culminate in the construction and field testing of gas-insulated, vapor-cooled transformers in three sizes.

The project is being cooperatively funded by EPRI, Niagara Mohawk Power Corp., Empire State Electric Energy Research Corp., and Westinghouse Electric Corp., who will conduct the research.

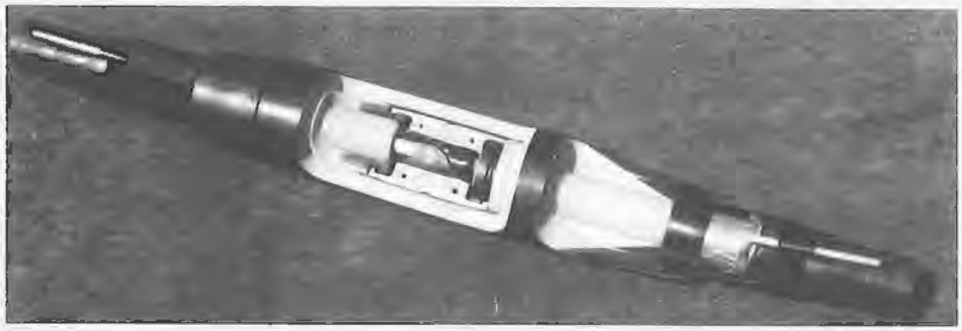
R&D Status Report
ELECTRICAL SYSTEMS DIVISION

John J. Dougherty, Director

Tangible results of research by the Electrical Systems Division have been achieved in a variety of projects. This report and those to follow throughout the year will highlight results that are of immediate value to utilities and their suppliers.

Publication of research results, however, simply states proven technical options that utilities can use to meet current and future energy demands. Since actual implementation is the ultimate measure of the division's R&D effort, we invite your questions or comments on the progress reported below. Above all, we urge your adoption and use of the results.

Figure 1 This factory premolded splice for use on 138-kV solid dielectric cable promises to reduce field installation time by as much as 70%, while increasing the reliability of cable joints.



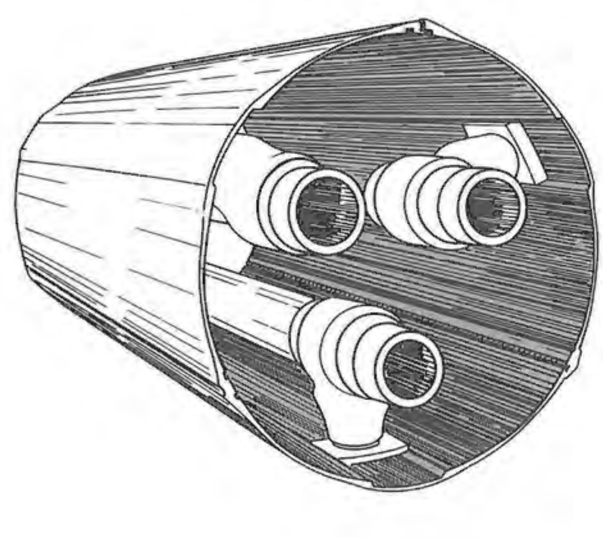
UNDERGROUND TRANSMISSION

A simplified splice for extruded high-voltage cable insulation has been completed under a contract with Esna Corp. (RP7815). This 138-kV, factory premolded splice (Figure 1) is expected to be tested at several utility installations this year and is also scheduled for long-term testing at Waltz Mill.

A utility's application of the splice should result in at least a two-thirds reduction in the time required to make field splices (10 man-hours versus 30–70 man-hours per phase for taped splices). The ability to factory-test the premolded splice should result in greater reliability of joints. (According to industry reports, the joint is where the overwhelming majority of field failures take place in extruded cables.) Hopefully, the availability of this simple, reliable splice will promote the use of more efficient and economic extruded dielectric cable systems. The final report has been published (EPRI EL-354).

A milestone in gas-insulated cable R&D has been reached with completion of the three-conductor compressed-gas cable project (RP7840) by Westinghouse Electric Corp. The final report (EPRI EL-389) shows that as much as a 15% savings in total installed cost can be realized over a rigid, isolated-phase, gas-insulated system at 345 kV. The most cost-effective development to come out of this project is the design of a segmented enclosure for the large-diameter tubes required on a three-conductor system. The method of fabrication is the key to this design—three extruded aluminum segments are welded longitudinally to form the tube enclosure (Figure 2).

Figure 2 A novel fabrication technique (longitudinal welding) for aluminum tubes forms a reliable, rigid enclosure for this 3-in-1, gas-insulated cable rated 345 kV.



This system can now be made commercially available. The full economic benefits will be realized as manufacturing and installation experience are acquired. A prototype installation is planned with a cooperating utility as a first step. *Program Manager: Ralph Samm*

OVERHEAD TRANSMISSION

Compact transmission line design has been high on the list of priorities at EPRI, the research having been initiated nearly three years ago because of the decreasing availability of rights-of-way for overhead transmission.

Now the feasibility of operating 115- and 138-kV lines with 3-ft (0.9 m) phase spacing has been demonstrated as a result of a research project (RP260) with Power Technologies, Inc. A reference book is now being published, giving detailed mechanical and electrical design concepts based on tests and operating experience obtained on a short 138-kV compact test line.

While the current edition of the National Electric Safety Code does not permit construction of lines with such small clearances, the practical limits of compact design have been shown. Hot line maintenance techniques have been demonstrated. Utility planners may now wish to consider this type of line design for solution of special problems where uprating of lower voltage circuits or constricted rights-of-way must be utilized (Figure 3).

Four utilities are presently using the results of this research to design compact lines for their systems. Another utility is extrapolating the 138-kV data for design of a compact 230-kV circuit. Final proof of the validity of this concept must await construction and operation of a prototype line by a utility.

The primary value of this research is in providing the utility industry with another alternative scheme for overhead transmission lines. Planners and designers can now consider compact lines for those special locations on their system where constricted rights-of-way will not permit construction of conventional circuit designs. Should a compact design meet the need, sound engineering data are now available on which to base line design and operation.

A second target of research in overhead transmission has been the problem of wake-induced conductor oscillations on bundled conductor lines. This project originated with the Electric Research Council. Violent motion is induced by the wind in bundled conductors, resulting in snapover with consequential hardware and tower damage and possible failure of the conductor. This problem was first discovered on 500-kV lines, but it extends to all the lines applying more than one conductor per phase.

A project recently completed by Alcoa Research Laboratories (RP119) has produced three useful results:

- Irregular spacing of nondamping spacers along the span will minimize weight-induced oscillations.
- Special spacer-dampers may not be required, as was first thought.
- A computer program has been developed to evaluate phase stability for existing lines and for new line design.

The significance of this accomplishment is that a simple and economic solution to a very complex problem has been found that is applicable to most cases. Utilities with bundled conductor lines are now benefiting from this research and manufacturers are recommending spacer applications based on these results. For example, Portland General Electric Co. is using the computer program to evaluate spacer applications to reduce wake-induced oscillations on their portion of the Pacific Northwest-Southwest 500-kV Intertie. Southern California Edison Co. has already employed the irregular spacing concept on its lines. Bonneville Power Administration and the Tennessee Valley Authority, as well as utilities along the Gulf Coast, are also using this concept.

It is estimated that approximately 20,000 mi (32,180 km) of lines using bundled conductors will be built between 1970 and 1980. If it is assumed that only 25% of these will be susceptible to subconductor oscillation problems, 100,000 conventional spacers could be employed instead of special spacer-dampers. Since conventional nondamping spacers that cost between \$10 and \$25 each may be used (compared with \$30–\$100 for spacer-dampers), a cost reduction of 60–75% may be realized. *Program Manager: Frank Young*

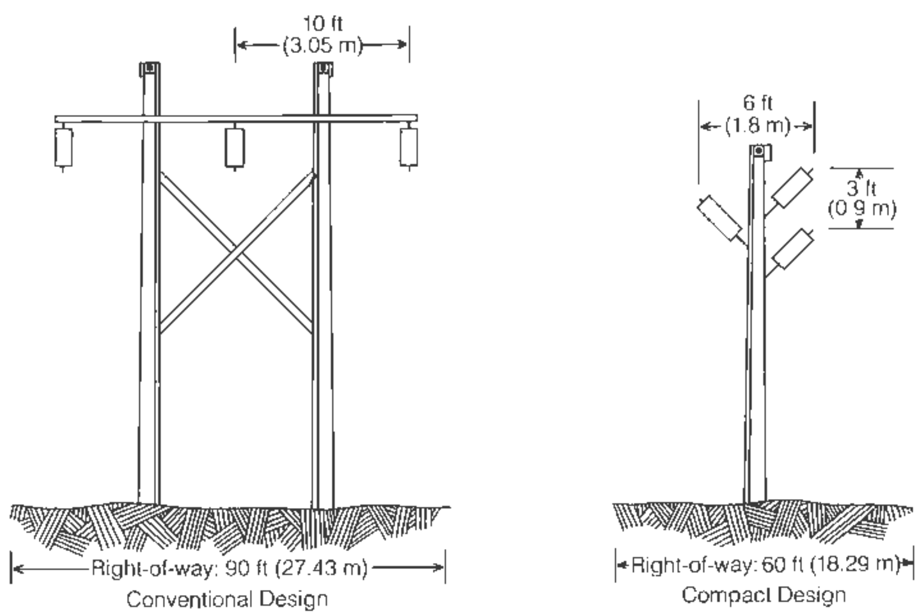


Figure 3 The advantage of compact overhead transmission line design shown should result in a significant reduction of rights-of-way needed for 138- and 230-kV lines. This should enable utilities to construct some lines at these voltage levels on city streets.

DISTRIBUTION

The corrosion of copper concentric neutral wires surrounding underground residential distribution (URD) cables is a problem of increasing concern to utilities. The cable life in corrosive areas may be reduced from an expected 35–40-year life to only 5 years. With over 100,000 mi (160,900 km) of URD cable now installed, and an additional 100,000 mi (160,900 km) to be installed within the next decade, the incidence of copper corrosion can be expected to increase. A project recently completed by General Cable Company (RP671) would eliminate this problem on new construction by applying a semiconducting jacket over the neutral wires to protect them from corrosion. This project was conducted in cooperation with Long Island Lighting Co. and Georgia Power Co.

By installing cables with the protective jacketed neutral in areas known to be corrosive, the subsequent high cost of replacing corroded cables can be avoided. This approach provides the industry with an immediate alternative to corrosion mitigation measures that have been used for copper neutral wires. The jacket also makes the cable safe for joint, random-lay construction with other utilities, while preserving the normal expected cable life of 35 or more years.

By avoiding eventual replacement of just 1% of 10,000 mi (16,090 km) of URD cable now being installed annually with bare concentric neutral the industry could realize a savings of $2.6 million. Additional savings of $3.3 million could be realized by increased application of joint, random-lay with other utilities, and an additional $2.5 million could be saved by eliminating damage to communication and other connected equipment. The total potential savings to the industry could approach $7.4 million annually. This type of cable is now being used by the Long Island Lighting Co. and Florida Power and Light Co.

A desirable new piece of equipment for distribution substations has been developed—a simple, compact, oilless, quiet, and rugged circuit breaker in the medium voltage class. All present 15–35-kV power circuit breakers have certain limitations that inhibit their use in restricted spaces, especially vaults. Oil breakers are large, and the use of oil, which is flammable, is undesirable for confined areas such as vaults. Vacuum interrupters are expensive high-technology devices that require precise and elaborate material, equipment, and process control techniques. Also, current chopping during vacuum interruption produces overvoltages that can damage other equipment. Air power circuit breakers are large, noisy, and emit undesirable arc products to the atmosphere.

A novel method of arc interruption that is especially well suited to distribution-class power circuit breakers has been developed under a research project (RP661) just completed by I-T-E. The unit employs a new breaker concept that uses the unique technology of spinning the fault current arc with a magnetic field to achieve interruption and the excellent insulating qualities of SF_6 gas.

The result is a breaker with features that are superior to oil, vacuum, and air power circuit breakers. The unit is expected to be competitive in price with oil power breakers, to contain a sealed interrupter having no internal adjustments, to require minimum maintenance and a low energy mechanism, and to be approximately one-half the weight of a comparable oil power breaker. Although it is suitable as either an outdoor or an indoor breaker, it is particularly attractive for application in metal-clad switchgear. The use of SF_6 gas as the insulating and interrupting medium will permit one module to be used in 15-, 25- or 35-kV applications.

A three-phase test model of a 15-kV, 25-kA distribution breaker has been assembled and tested; tests on single-phase models have achieved interruption at 40,000 A. The contractor is preparing designs for commercial prototype production. *Program Manager: Richard Steiner*

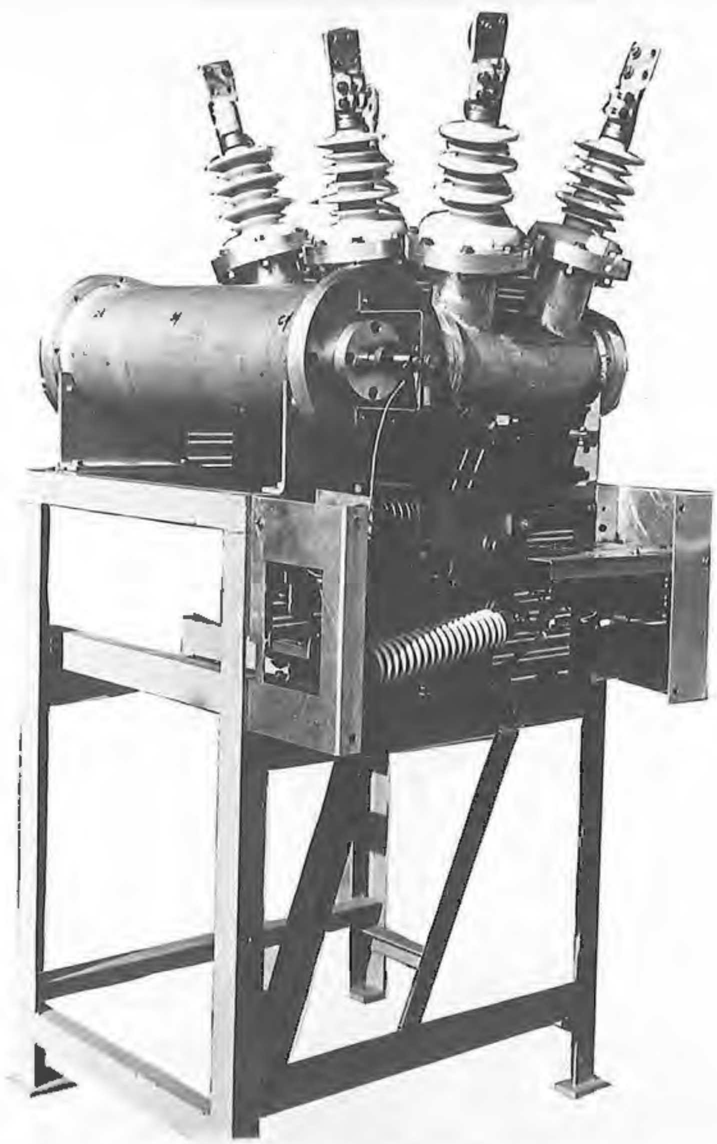


Figure 4 Laboratory model of three-phase, SF_6 magnetic interrupter developed under RP661 by I-T-E.

R&D Status Report
ENERGY ANALYSIS AND ENVIRONMENT DIVISION

René Malès, Director

DEFINING DISTRIBUTION OF POLLUTANTS

An important ongoing effort of the Physical Factors Program in the Environmental Assessment Department concerns the identification, characterization, and monitoring of pollutants resulting from electric power production. The ultimate goal is to define the distribution of pollutants in the environment. Such knowledge is essential for evaluating health effects and for studying transport phenomena, including reaction mechanisms.

At present, the identification, characterization, and monitoring subprogram is supporting 16 research projects—8 at universities, 7 at private research organizations, and 1 with a government research group. Expenditures for 1977 will amount to approximately $1 million, with about 60% going to universities, 35% to private research groups, and the remaining 5% to a national laboratory. Studies have focused almost entirely on atmospheric pollutants from coal-burning facilities and will continue to do so for the next few years. However, research is increasingly being directed toward pollutants in terrestrial and aquatic environments and pollutants derived from fuels other than coal.

The subprogram has two main aspects: research on sampling and analytic methods; and field measurements. Sampling and analytic techniques are being studied to assess the reliability of existing procedures and to develop new approaches. The measurement effort deals not only with pollutants from power plants but also with those from nonanthropogenic and non-power plant sources in an effort to define more accurately the utility industry's contribution to the environmental inventory. The three projects described below indicate the types of research being supported through the subprogram.

In a study on sulfur dioxide interferences in the measurement of ambient particulate sulfates (RP262), Radian Corp. evaluated the magnitude of error in measuring sulfate concentrations with the use of high-volume filters. The specific error suspected arose from the possibility that atmospheric SO_2 might be forming sulfates on the filter itself. Such formation would, of course, give too high an estimate of atmospheric sulfate, due to the combined atmospheric concentration, and the secondary formation on the filter. If secondary sulfate formation is significant, existing sulfate data are suspect, and many health effects studies are without firm foundation. In view of the seriousness of the issue, an evaluation of measuring error is a high priority.

The research entailed the exposure of commercial filter materials to a flow of air of known SO_2 concentration, humidity, temperature, and, in some instances, particulate matter. The filters were analyzed for both SO_2 and sulfate. The research (Final Report, EPRI-262) demonstrated that SO_2 on filters will convert to sulfate in amounts equivalent to 1.6 to 8.9 $\mu g/m^3$, for a 24-hour sample. For 2-hour samples, the interference from conversion is especially severe because most conversion occurs within the first few hours of sampling. Temperature and concentration of SO_2 are the two major variables that affect secondary sulfate formation, the formation being favored by low temperature and a high level of SO_2. Fortunately, pretreatment of filters can reduce the interference problem. The problem of more sulfate being measured than actually exists is real. However, meaningful interference probably does not affect values over 10 $\mu g/m^3$. High sulfate values, therefore, are probably not significantly suspect. Conversely, low values may indicate significant error.

Two projects are under way to develop laser units for remote measurement of atmospheric pollutants. Stanford Research Institute (SRI) is developing a mobile laser instrument for making field measurements of SO_2, NO_2, and O_3. Because of increasing concern over air quality, the electric power industry needs better and less expensive methods of measuring atmospheric quality for such purposes as determining the best plant sites and monitoring effluents from existing plants. The measurement or monitoring of stack emissions is a key factor in judging air quality, in designing control devices, and in understanding the chemical reactions that occur in the atmosphere, particularly those within plumes.

Present measuring techniques depend either on ground stations (which give, at best, only an indirect indication of what is at higher levels of the atmosphere) or on aircraft (which are limited by cost, weather, and flight restrictions). What is needed is a way to measure atmospheric constituents from the ground under all weather conditions. A laser device has such capability. A basic laser instrument has been developed by SRI. The current work is aimed at making the device and supporting computation equipment both mobile and field operational. Although a number of laser units are already in operation, the one being developed with EPRI support is unique in that it can operate under all weather conditions, day or night, and from the ground can analyze the atmosphere over any discrete interval (e.g., between 1000 and 1500 feet) from ground level to about 7000 feet. The mobile unit should be operational in early 1978. The other project, a demonstration of remote air pollution measurement capability (RP486) with Stanford University, is aimed at developing a laser unit that is interchangeable with the SRI device and that will operate at shorter wavelengths than the SRI device. The advantage of the shorter wavelength unit is better analytic discrimination and less interference.

New York University is working on the sources and tissue deposition of trace elements in urban aerosols (RP439) in an effort to: (1) provide data on present air quality in New York City in terms of present fuel use; (2) identify the sources of suspended particulate matter in the atmosphere and the percentage contributed by source—the main ones being automobile, fuel oil furnaces, incinerators, and natural sources; and (3) define any relation that may exist between trace element content in human tissues and that in the atmosphere. Many urban areas face the possibility of having to change from one fuel to another in the near future, and the effect of this change on atmospheric quality is a real concern. However, the effect cannot be assessed without background data for comparison. The need for such data is the rationale behind the first goal.

The rationale for the second goal centers on control strategy. An effective control strategy needs to be predicated on accurate information covering the extent to which utilities contribute to the total atmospheric loading of pollutants. Existing emission inventories, especially those for New York City, are of only limited use in providing such information. The research in this project is providing a much more direct means, based on actual collection of ambient pollutants, of defining air quality and of indicating the amount of pollutants contributed by individual sources.

The interest in the third goal is really the focus of almost all air quality programs, that is, what effect does air quality have on humans? Certainly the relation between changes in air quality and the incorporation of pollutants in tissue has profound implication for any type of control strategy.

In this study, samples have been collected at five sites over a period of two years and analyzed for a variety of physical and chemical parameters. The data were then analyzed statistically, using correlation-regression analysis and factor analysis to identify key elements that would be indicative of a particular source. The tissue work involved collecting tissue (mainly from kidney, liver, respiratory organs) plus blood and bone from persons who died suddenly. Sudden-death victims were selected in order to eliminate the possibility of having tissue samples that might be contaminated from a long-term illness. Tissues were then routinely analyzed for the same list of elements as in the air quality work.

Results include background data and source identification (Final Report, EPRI-117). The study identified the automobile and natural sources as making the greatest contribution—30% each—to atmospheric particulate loading. Fuel oil burning, including that in power plants, contributes 11%. Since 1969 the automobile contribution has doubled, the fuel-oil contribution halved. Tissue studies show that concentrations of chromium, nickel, and lead in air correlate with those in lung and lymph node tissue. Also, the amounts of cadmium and lead in tissue relate to incipient pathological symptoms in humans.

Within the identification, characterization, and monitoring subprogram, new studies will be directed toward atmospheric organics, problems related to waste (ash and sludge) disposal, and pollutants arising from coal conversion processes. Research in the first two areas has already begun. Emphasis on air pollution will remain, while interest in other facets of environmental damage are receiving more attention. *Program Manager: Ralph Perhac*

FORECASTING REGIONAL FUEL SUPPLY AND PRICE

The Energy Supply Studies Program provides supply curves and analysis for all fuels and sources of energy. Such information on fuel prices and availability plays an important role in the evaluation of R&D options for power generation. In the case of oil and natural gas, the supply forecasts serve a dual purpose. They throw light on the viability of technological options, such as the fuel cell, and since oil and natural gas are electricity's most important competitors in many markets, their projections of price and availability are important determinants of electricity requirements. A previous report (JOURNAL, November 1976) described two projects, RP436 and RP665, which reviewed oil and natural gas supply modeling efforts that determined the state of existing knowledge.

A study on domestic oil and gas supply (RP944) will develop a mechanism for producing credible, regionally disaggregated projections of domestic oil and gas prices and quantities over the next 25 years. The proposed research will synthesize specific elements from selected models (reported in the above projects) and augment these with new models to provide a computerized evaluation system. This system will allow EPRI analysts and others to project regional oil and gas supply and transmission patterns under a variety of alternative assumptions.

To construct this system, the researchers will extend and refine the models of offshore oil and gas supply and examine the potential of applying methods to onshore "frontier" areas, whose economic and resource development considerations are operationally similar to the offshore areas. The prospects for supplemental and synthetic gas supplies will be examined from the standpoint of the likely timing, regional dispersion, volume of gas to be produced, and the economics of distribution questions needed for analysis of these new supplies. The feasibility of extending methodologies to examine the link between the marketplace of oil and natural gas and the resources allotted to exploration and drilling will be determined. The research will modify a linear programming model of the natural gas pipeline transmission network to permit regional projections of supply to the end user. The oil and natural gas pipeline studies are most important in view of the possibilities for reversing existing lines and building new lines to accommodate Alaskan crude oil and natural gas, thus perhaps radically changing regional patterns.

The contractor, Mathematica, Inc., and subcontractors, Institute of Gas Technology and the University of Southern California, are developing a detailed design for the research in this project. It includes methodology evaluation and the selection of particular elements of existing methodologies for adaptation in new gas and oil evaluation systems, as well as the development of new analytic elements where existing methods are deemed inappropriate. An important component of the design task is the specification of linkages between model components. The output of this phase will be a more refined design of the remainder of the research. Major emphasis in the research will be put on regional exploration activity models. Methodologies that have been used by the FEA and others will be synthesized to modify existing models for examining the relationship between risk and return in order to develop disaggregated projections of gas discovery and production.

A major portion of the research will be devoted to implementing the oil and natural gas analysis systems so that analysts may examine alternative assumptions and future projects. The analysis system will be applied to present forecasts of regionally disaggregated oil and gas supply for the next 25 years. The researchers will develop alternative scenarios that describe the likely states of nature over the next 25 years for the key input parameters.

Completion of this project will provide the Supply Studies Program with the mechanism to forecast gas and oil supplies. This will be coupled with a supply analysis of nuclear fuels, coal, and other new technologies to provide the production side of the supply and demand picture. The analysis in this study will be aided by research in other subprograms. The supporting resources subprogram, for example, will provide supply information on input, such as water, capital, labor, and other materials. The energy delivery and storage subprogram will analyze related transportation problems, such as oil tanker characteristics and LNG transport. The result will be consistent sets of supply curves that will allow analysis of new technologies and projections of future energy pictures. *Project Manager: Rex Riley*

ANALYZING RESIDENTIAL ENERGY USE

The timing of this status report on residential sector research is appropriate since two major projects were recently completed and two others initiated. This allows examination of the connections between two links in the research project chain as opposed to viewing an isolated link where the direction of research is less visible and the results more tentative.

The recently completed projects were RP333 on the assessment of energy modeling (*Long-Range Electric Energy Demand Studies*, EA-221), and RP431 on the development of models to aid in forecasting residential energy use (*Residential Demand for Energy*, EA-235). A number of conclusions from the projects are useful for immediate forecasting application.

RP333 demonstrated that the selection of historic data periods often has a dramatic effect on forecasting performance. Based on tests conducted for the residential sector, RP333 found that two types of models yielded relatively strong forecasting performances. The first was characterized by a detailed specification of demographic and meteorological variables in addition to income and the prices of electricity and substitute fuels. The second approach used an estimation technique that captured much of the inherent regional variation among states.

RP431 demonstrated the importance of energy prices in determining the amount of electricity households consume. The results were especially strong in view of the extensive methodological and data development conducted in the project. The study established the practical importance of properly modeling declining block tariffs and concluded that the long-run residential price elasticity of demand for electricity may not be as large as previous studies indicated.

The objectives of RP333 were to provide points of reference with which EPRI-sponsored models may be compared and to provide "place-holder" models for forecasting while EPRI-sponsored models were under development. The project began with the development of a set of model selection criteria that led to the evaluation of four residential, one commercial, and three industrial econometric models. Given these models, an appropriate common data base was constructed and the parameters of the models estimated. The models were then subjected to various formal and informal tests concerning their ex-ante forecasting capabilities.

In addition to basic statistical tests concerning explanatory power of the estimated equations, the models were also analyzed in terms of parameter stability, appropriateness of specification, treatment of the error structure, and practical usefulness for forecasting application. The models were further analyzed in terms of forecasting and backcasting accuracy over various historic data periods. In addition, an annotated bibliography of electricity demand studies was produced. The results of the study led to the selection of a particular commercial sector kilowatthour model to be used in the current EAE Division's in-house energy forecast to the year 2000. These forecasts will assist EPRI in its R&D planning.

In the residential sector, the results of RP333 concerning various treatments of the error structure led to the use of a particular parameter estimation technique for the models developed under RP431. The EPRI technical staff subsequently selected one of the residential models from RP431 for integration into the EAE Division's forecasting model.

The principal objective of RP431 was to construct detailed time series data for major household appliances and declining block rate structures for electricity. Both data series covered 48 states for the years 1956–1972. Appliance data were constructed from *Merchandising Week* and Bureau of the Census sources, while the rate structure data were aggregated to the state level from actual utility rate structures. The data base gives EPRI the capability to conduct detailed analysis at the state level, which may then be aggregated into national forecasts. The study also maintained much of the disaggregate data concerning individual utility service areas.

The continuing development of those models will focus on improving model specifications, generalizing estimation techniques to better account for regional diversity in the parameters, improving the treatment of interfuel substitution among natural gas, oil, and electricity, and improving several aspects of the analysis of declining block rate structures, such as residential electricity taxes. These models ultimately will allow EPRI's Energy Demand and Conservation Program to address such questions as the effects of natural gas curtailment and deregulation; regional trends in variables, such as income, population, and urbanization; and the market penetration of various space-conditioning systems.

The final reports of RP431 and RP333 both noted that the aggregate analysis of household energy consumption decisions was limited by aggregation problems, which often mask the true behavior of individual households. In response to this need, research on patterns of energy use by electrical appliance (RP576) was initiated as a joint EPRI–FEA project in 1975. This project began with a survey by personal interview of 2000 randomly sampled households. From the primary survey, 150 households were selected, which had an average of 8 major electric appliances individually metered to record monthly kWh usage. Using the RP576 survey data as well as the data collected under the FEA–Northeast Utilities Time-of-Day Pricing Experiment, RP1005 was initiated to analyze major appliance and fuel choice decisions by households. RP1005 also will focus on the development and application of statistical techniques to combine survey data sets based on different sampling distributions and experimental objectives but applying to the same geographic area. A number of cross-section data sets are too small to be of general usefulness in isolation but may provide a rich information base for household energy consumption analysis if successfully aggregated to meet the needs of EPRI.

A second aggregation question in this area is how to utilize simultaneously the information contained in cross-section survey data and aggregate state data such as that collected in RP431. The project will analyze the applicability of a variety of discrete choice models to the problem of forecasting the demand for new and existing energy-using equipment. These models explicitly recognize that many household appliance options, such as space heating, result in the selection of one fuel type. The resulting appliance forecasts ultimately will be used in energy consumption and load forecasting models. The RP576 data also are being used by the EPRI technical staff in an in-house study of the discrete choice modeling of space and water heating fuel decisions.

The second residential sector project recently initiated is a study on the analysis of load management experiment data (RP1006). This project will assess data sets forthcoming from load management and time-of-day pricing experiments for their usefulness to EPRI project areas, such as appliance stock forecasting, the demand for new goods, and load forecasting. As a by-product the study also will examine the quality of the data in terms of completeness, appropriateness of sampling procedures, and experimental design. In addition, the study will evaluate the usefulness of the data for policy inference by individual utilities and public institutions. It is expected that these experiments will provide useful cross-section survey data and that they will allow detailed analysis of consumer responsiveness to time-of-day and seasonal pricing and the efficacy of various load management devices. *Project Manager: James Boyd*

R&D Status Report
NUCLEAR POWER DIVISION

Milton Levenson, Director

SURFACE CONDENSER LEAKAGE

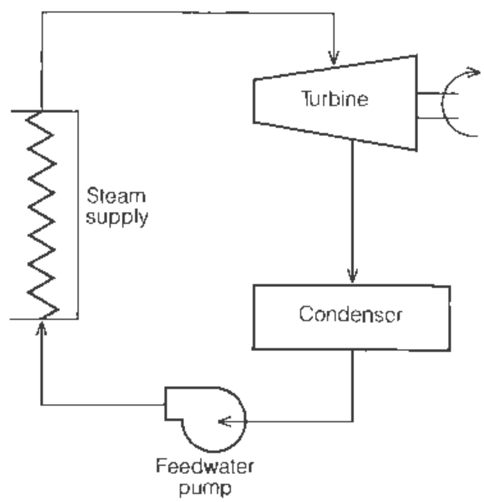
The main surface condenser is a critical component in the steam cycle of any steam electric power plant (Figure 1). This large tube-type heat exchanger functions as a heat sink for condensing the exhaust steam from the power turbines and as a deaerator of the resulting condensate. In functioning as a heat sink, the condenser is the only boundary between the high-purity water in the steam cycle and the relatively impure cooling water (e.g., lake, river, ocean, or cooling-tower water).

The integrity of the condenser becomes a crucial factor in the reliability of a power plant when considering the plant productivity loss from repairs to condenser leaks and, probably more important, the deterioration of other components (e.g. steam generators) in the steam cycle as a result of impurities in the condenser leakage.

The possibilities for leakage into the condenser are extensive when one considers that today's large power plants have condensers with more than 60,000 tubes, and that each condenser is comparable in size with a house. Tube failures can result from a number of causes. Mechanical malfunctions, such as thrown turbine blades or other objects falling on the tubes, tube vibration, and broken baffles allowing steam to impinge directly on some of the tubes, are prominent causes of tube failures. Tube corrosion and/or erosion constitute another class of failure mechanisms.

In general, a condenser's susceptibility to the various mechanisms for leakage is a function of several variables and combinations of those variables, including cooling-water environment, condenser design, materials of construction, steam-side water chemistry, and operation and maintenance procedures.

Figure 1 A diagram of the steam cycle in any steam-electric power plant, whether fossil-fired or nuclear, showing the position of the condenser.



The Bechtel study

In order to determine what experience operating power plants have actually had with condenser tube leakage, EPRI contracted with Bechtel Corp. for an industry field survey and literature search (RP624). The Bechtel study addresses several areas related to condenser tube leakage, including design, materials, chemistry, operation, and maintenance. The field survey concentrated on large fossil-fueled plants, nuclear plants, and plants having condensers tubed with titanium. During the survey, 30 power stations with 76 generating units (61 fossil, 9 PWR, 6 BWR) were visited. The 76-unit condensers included 116 condenser shells containing a total of 2,281,510 tubes with a total surface area of 23,189,000 ft² (215,433 m²). The median age of the generating units was 12.1 yr, and the median generating capacity, 476 MW.

A comprehensive field survey form was used for the collection of all pertinent data. The surveys were conducted by multidiscipline teams of 1–3 engineers.

One area of prime importance in the Bechtel work is the analysis of the large volume of condenser tube failure data collected in the field survey. In order to interpret these data, the tubes in a particular condenser were grouped into several tubesets according to their service function. Examples of such tubesets are air removal sections, condensing sections, steam impingement sections, or combinations of these. Tubing failure rates were then calculated as a function of tubeset, tubing material, cooling-water conditions, failure mechanisms, condenser design, condenser size, and many other parameters about which data were collected in the field survey. The failure rate calculation used in this study was used previously by Newton and Burkett *(1)* in a similar application and is defined as the percent of tubes failed (plugged) per 10,000 service hours:

$$\text{Failure rate} = \frac{\%\ \text{Tubes plugged}}{\text{Service hours} \times 10^{-4}}$$

Table 1 shows the distribution of tubesets surveyed by material and cooling-water conditions.

Table 1
FIELD SURVEY TUBESET DISTRIBUTION

Material	Fresh Water	Tower Water	Ocean Water	Total (tubesets/tubes)
	Number of Tubesets			
Admiralty	102	16	1	119/649,506
90–10 CuNi	17	4	56	77/499,183
70–30 CuNi	0	12	53	65/104,096
CuNi (unspecified)	4	0	0	4/512
Aluminum brass	0	0	37	37/333,203
Aluminum bronze	0	0	12	12/88,550
304 stainless steel	95	13	0	108/405,128
316 stainless steel	8	0	9	17/39,325
Titanium	8	0	23	31/162,007
Total	234	45	191	470/2,281,510

Comparison of tubeset performance

Probability versus failure rate curves can be drawn for many of the tubeset service environments. These curves indicate the probability that a particular tubeset will have a given failure rate. They can be used in conjunction with operating time versus failure rate curves to indicate whether or not a particular tubeset will have a desired service life. For example, if 300,000 operating hours are assumed optimal for a 40-yr life and if a 10% incidence of plugged tubes is considered to be the criterion for retubing, then the operating time versus failure rate will show that a failure rate of 0.333 or less is required over a 40-yr service life. The probability curve will indicate the chance of obtaining this failure rate. Figure 2a is an example of how the two sets of curves (probability versus failure rate and operating time versus failure rate) can be used to compare the performance of different tubing materials. Tubesets that were identified specifically as air removal sections or steam impingement sections are not included in these comparisons. The comparison shown in Figure 2a is for titanium, aluminum brass, 90–10 copper-nickel, and aluminum bronze tubes used in a seawater environment. Based on data collected in the field survey, the graph indicates that titanium has a 94% probability of attaining a 40-yr life with 10% plugged tubes, aluminum brass has a 47% probability, 90–10 copper-nickel has 40%, and aluminum bronze has a 33% probability.

When this same type of comparison is made for the three most prominent tubing materials in freshwater service (i.e., 90–10 copper-nickel, admiralty brass, and 304 stainless steel), the result is a greater than 90% probability for all three of these materials to attain a 40-yr life with less than 10% plugged tubes.

These two comparisons indicate that selection of tubing material is a more critical factor for good condenser performance in seawater or other severe cooling-water service than in freshwater service.

It should be pointed out that the probabilities used in the above comparisons are based on failure rates due to all failure mechanisms and that mechanical failures can be independent of the type of tubing materials used. Also, as shown in Figure 2b, certain operational factors can play a role in the performance of tubing materials. Figure 2b indicates that 90–10 copper-nickel performance in seawater can be expected to improve with ferrous sulphate additions.

The location of tubes within the condenser can also play an important role in the performance of the tubes. Figure 2c shows that admiralty brass used in the main body of the condenser has a good performance record in fresh cooling waters, but when the performance of admiralty brass used only in the air removal section of condensers is examined, it can be seen that the performance is relatively poor, with only a 27% probability of a 40-yr life with no more than 10% plugged tubes. The poor performance of admiralty brass in air removal sections is due primarily to its susceptibility to steam-side ammonia attack. The ammonia is generated from the feedwater treatment chemicals and tends to concentrate in the air removal section.

The work done under this project can provide the utilities with a basis for making decisions on the type of tubing materials to use in their specific application. The study also indicates that a large percentage of condenser tube failures encountered in the field survey were mechanical or design-related. It discusses what existing units are doing to cope with these problems and what design considerations would be useful in avoiding these problems in new condensers.

A large body of operating experience data has been collected in this study, and more importantly, methods were developed for using the data to compare the reliability of various condenser tubing materials under different service conditions. At the same time, there are many aspects of condenser performance where sufficient information is not readily available to draw meaningful conclusions. The power plants represent an ideal proving ground for large components such as condensers, but the task of reconstructing the performance history of these components a year or more after the fact has proven to be difficult, if not impossible. If plant operating experience is to be used as an effective tool for assessing large component performance, a means must be established for systematically recording this experience and making it readily accessible for analysis.

Literature survey

The literature survey in the Bechtel study produced a final bibliography containing 391 references related to condensers. This bibliography will be listed in the final report on the findings of the study and coded by keywords. Reference sources include the Engineering Index, National Technical Information Service Index, Copper Development Associates, industry contacts, and articles obtained for review. Many of the articles obtained through the literature search will be referenced in the text of the final report. *Project Manager: William Lavallee*

Reference

1. U.S. Department of the Interior. *Survey of Condenser Tube Life in Salt Water Service*. Washington, D.C.: The Office of Saline Water, Report No. 278 (August 1967).

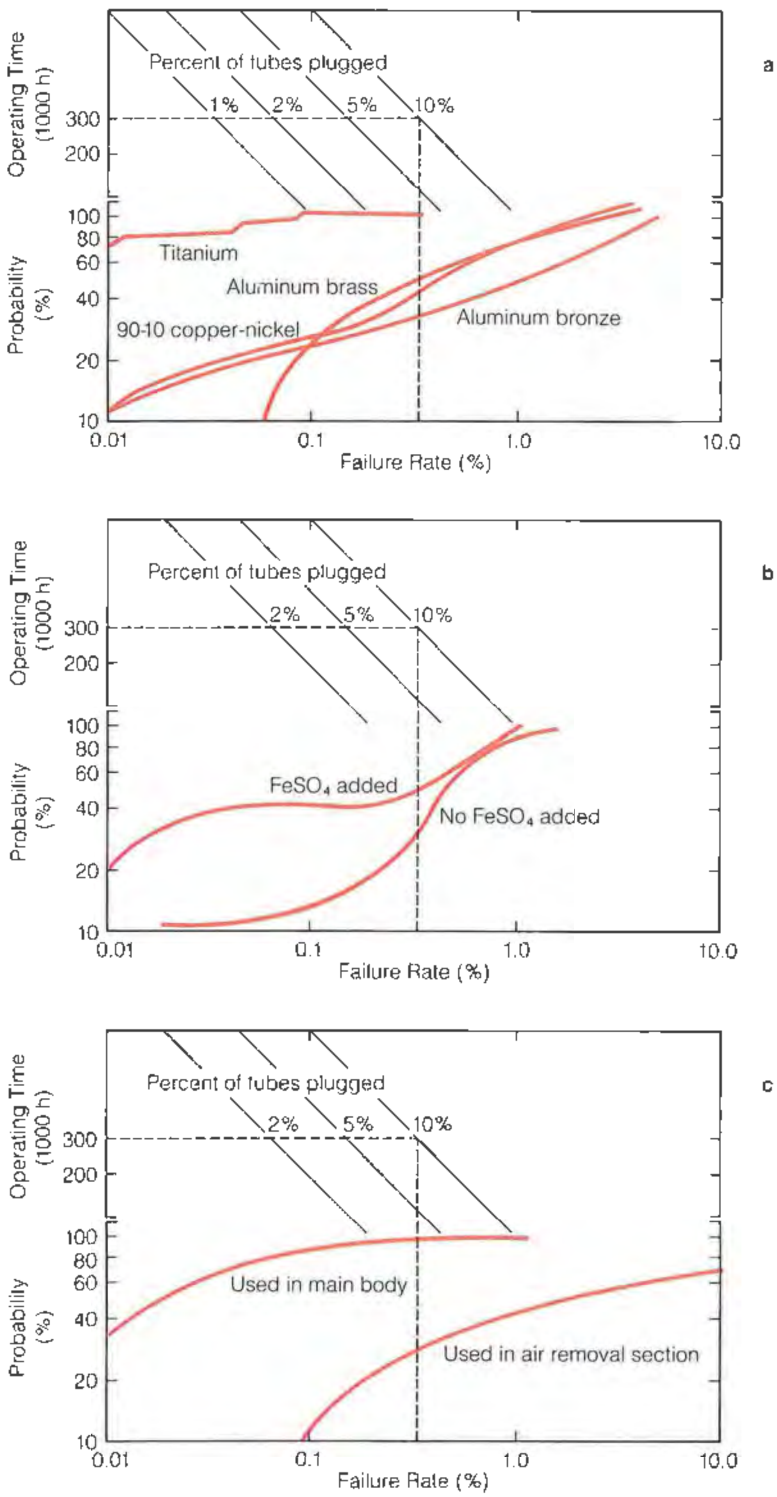


Figure 2 Failure rate versus probability curves for three situations of condenser tube performance: (a) shows the behavior of titanium, aluminum brass, 90–10 copper-nickel, and aluminum bronze in seawater; (b) shows the effect of adding ferrous sulfate to 90–10 copper-nickel for seawater service; (c) indicates the difference in behavior of admiralty brass depends on its functional location within the condenser.

POOL SWELL IN PRESSURE SUPPRESSION SYSTEMS

For the past 20 months EPRI has been investigating the phenomenon of pool swell in BWR Mark I containment wetwells (Figure 3) and is continuing to improve the predictive methods, as well as to describe the structural response to pool swell. There is strong indication that the structural feedback effect on the phenomenon could affect the loads experienced. The four areas of study are:

- Hydrodynamic analyses of pressure suppression, or pool swell (RP693-2, with Jaycor)
- Multiple downcomer pool-swell tests (RP693-1, with Stanford Research Institute)
- Fluid-structure interaction analysis (RP812, with Science Applications, Inc.; Marc Analysis Research Corp.; and Lockheed Missiles & Space Co., Inc., Palo Alto Research Laboratory)
- Water impact tests (RP817, with Developmental Sciences, Inc.)

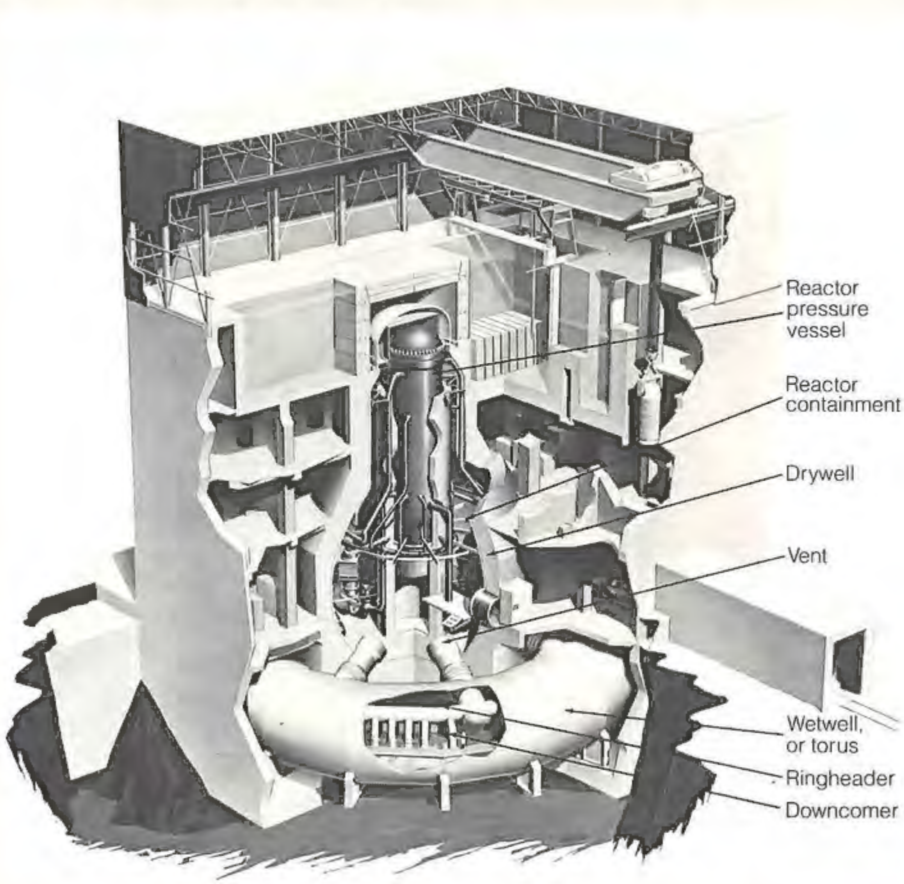
The hydrodynamic analyses discussion that follows documents the model development that has been performed and validated by early two-dimensional Mark I pool-swell tests. Future work in this area will extend the predictive methods to three dimensions, with a data base for validation available from the multiple downcomer pool-swell tests.

EPRI's study of fluid-structure interaction is presently focused on the ringheader response to pool swell impact. The nonrigid response of the structure may in fact mitigate the loading on the structure. To clarify the interaction, both analytic and experimental efforts are under way.

Hydrodynamic analyses

EPRI is currently sponsoring research to quantify the loads in a Mark I containment system during a postulated LOCA. This project will develop and verify (by comparison with experimental data) numerical models to simulate pool swell. The effort has produced two numerical models (codes) that together calculate the kinematics and the dynamics of the pool swell from initial drywell pressurization until shortly after ringheader impact. Two codes were developed because two flow regimes were identified with the aid of laboratory observations: the distinctly three-dimensional flow field during and shortly after the vent-clearing process, and the essentially two-dimensional flow in the intermediate and late stages of bubble growth. The VENT-3 code covers the period from the initial drywell pressurization to the

Figure 3 Isometric cutaway of a typical Mark I BWR shows relationship of the pear-shaped drywell containing the reactor to the doughnut-shaped wetwell below, whose function is to protect containment integrity against the possibility of sudden overpressurization in case of a release of steam during a postulated LOCA.



time when water in the downcomer is completely expelled. In this code, the transient, three-dimensional nature of the flow is fully taken into account. Future work will include development of a three-dimensional code to simulate the nonuniform pool swell that is expected to occur in a Mark I prototype.

Multiple downcomer pool-swell tests

The purpose of the tests is to investigate at reduced scale (1 : 12) the multidimensional hydrodynamic effects during the early pool-swell phase in a Mark I pressure suppression system following a postulated LOCA. As yet, only single downcomer-pair (two-dimensional) models have been tested, and the three-dimensional pool-swell effects have not been experimentally quantified. The project is focusing on quantification of this phenomenon and the resultant hydrodynamic loads. A sufficient data base will be generated to permit validation of a predictive method, as discussed in the previous section.

The planned test model will include 12 downcomer pairs so that various boundary conditions may be simulated (Figure 4). The torus simulation will be a transparent right circular cylinder with clear plastic downcomers to allow for photography of front and side views.

The basic test format for the proposed multiple downcomer model will involve a rapid pressurization of a simulated drywell, a blowdown through the vent system that connects the drywell to the wetwell, and the subsequent pool swell in response to the blowdown.

In the course of our research it has become evident that the original scaling law derived for incompressible fluid flow was not appropriate for the compressible airflow through the vent system during the dynamic blowdown process. A new scaling law must be derived that is dependent on the flow characteristic of the particular vent system. For the Mark I system where the flow is branched and turned a number of times in the ringheader and downcomers, a detailed flow characteristic study is required. Although the exact scope of this research is difficult to assess, plans are that two partial vent systems (one vent with six downcomer pairs) of different scales will be flow-tested in air. The partial vent systems will be subjected to airflow over a wide range of flow rates prior to testing on the wetwell model. The measured flow rate of each downcomer will then be correlated to pressure measurements at various points along the partial vent system. These tests are required before the orifices for flow scaling the wetwell model can be specified. Instrumentation in the early flow characteristics study will include pressure transducers, velocity probes, and flow-measuring devices. During the torus model dynamic blowdown tests, a high-speed movie camera, pressure transducers, and load cells will be used. The present plan calls for force measurement by load cells and for pressure measurements in the drywell at the downcomer exit, in the wetwell air volume, and at the wetted boundary in the lower half of the torus. High-speed movies will examine hydrodynamic response of the water from both the front and the side.

The data base generated by this experimental series will be a reference data base for the computer code development described earlier.

Fluid-structure interaction analysis

A parallel effort to investigate the effects of fluid-structure interaction in the Mark I pressure suppression system under postulated LOCA conditions was initiated in July 1976 with preliminary effort directed toward a determination of the response of the ringheader under pool-swell impact loading. Various computation techniques are being employed to perform a coupled fluid-structure impact analysis of the ringheader under idealized conditions. This project is closely coordinated with a parallel experimental program investigating hydrodynamic impact of simple ringheader models.

The primary objectives are to assess the effects of ringheader flexibility on pressure loads sustained during water impact and to investigate the applicability of various computation methods for coupled, fluid-structure impact analysis.

A simple fluid-structure model is considered in which the ringheader is modeled as a long, thin cylindrical shell (without downcomers) subjected to normal impact by a large body of water. The cylindrical shell, initially at rest, is located just above a large mass of water moving upward with an initial uniform velocity. The diameter and thickness of the prototype ringheader are taken as 58 in (1.47 m) and 0.25 in (6.35 mm), respectively. Calculations will be performed for

Figure 4 A model of a section of the wetwell and its internal components to be used in water impact tests to confirm the ability of the structure to withstand the hydrodynamic forces that would be exerted during pool swell.

various initial water impact velocities. In addition, analyses will be performed for geometrically scaled shells for comparison with scale model impact experiments.

The calculations will be performed in two phases. In the initial set, the cylindrical shell will be assumed to be perfectly rigid. The results of the analytic techniques utilized will be compared with each other and with available experimental data. In the second set of calculations, flexibility of the shell will be introduced. Comparison of pressure histories and impulse during impact for both the rigid and flexible shells will be used to assess the effects of fluid-structure interaction.

Water impact tests

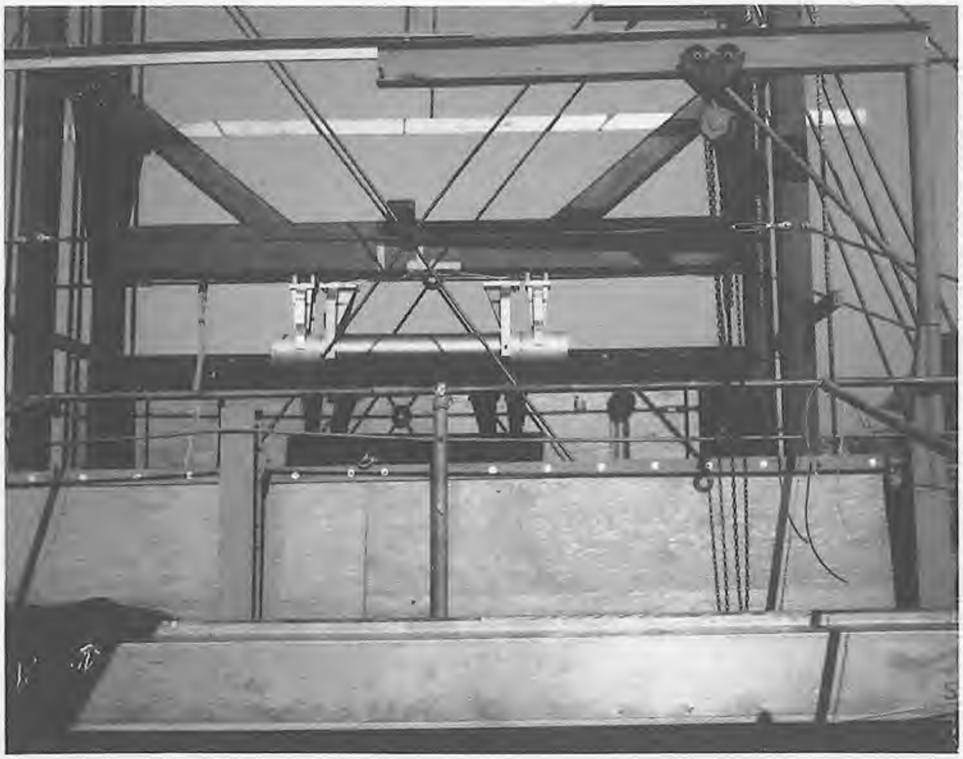
A series of water impact tests is being conducted to provide data for comparison with analytic results. The tests consist of driving cylindrical steel models of the ringheader onto a surface of water. Models at two nominal scales (0.30 and 0.15) are being tested to provide data to evaluate scaling relationships. The models are instrumented to measure impact pressure, forces, strains, and accelerations. Impact pressures measured on thin-walled scale models will be compared with pressures on thick-walled models to assess the magnitude of load mitigation from fluid-structure interaction.

To meet this objective, both the models and the loading technique are as simple as possible, while still maintaining the essential characteristics of the prototype system. This ensures that investigation of scaling relationships and correlations with analytic results will not be clouded by second-order complexities.

The models are simple versions of the straight segment of ringheader pipe between support columns: cylindrical shells with simple supports at the ends and no downcomers. Duplication of the actual support conditions (continuous over support columns) would be difficult. The simple model supports are adequate for the purpose of estimating fluid-structure effects and are well characterized for comparisons with analyses.

Since pool-swell tests have shown that the water surface is almost flat in the local region of ringheader impact, a flat surface of water is being conservatively used in the early tests. Also, for ease of testing, the models will be driven at constant velocity into a stagnant pool of water. It is recognized that this simplified impact condition does not account for the presence of discharge air bubbles in a real pool swell, which would tend to decrease the loading by introducing a nearby free surface that reduces the effective mass

Figure 5 A complex moving-carriage system has been devised for the water impact tests of models of the ringheader. For experimental convenience, instead of jets of water striking the model, the model itself is driven into a stagnant pool of water; the effect is the same provided the velocity is the same.



of the impacting water and accounts for the compressibility of the air bubbles.

As shown in Figure 5, the models are attached from below to a stiff, massive carriage on rollers and driven downward into a pool of water 4 ft deep and 8 ft wide (1.2 m by 2.4 m). The test assembly is accelerated to the specified test velocity at impact by a chain and sprocket network driven by an electric motor. The drive system keeps the model at virtually constant velocity during water impact. Transducers are located optimally to monitor pressure and strain distribution over the surface of the models, total forces at the model supports, and accelerations of the model centerline and supports during impact. About 18 transducers are installed on each rigid model and about 25 on each shell model.

The measurement of impact pressures on the thin shell walls requires special care. The piezoresistive transducers selected are small and light enough not to alter appreciably the dynamic response of the shell. They are also insensitive to the effects of acceleration and thermal drift that often plague water impact pressure measurements.

The models are being tested over a range of impact velocities from about 6 ft/s to 30 ft/s (1.8–9.2 m/s). The shell models are driven repeatedly into the water at increasing velocities until the level of incipient permanent deformation is reached. If results show that tests at higher velocities are needed, spare models will be used. Rigid-model tests can be repeated with the same model over the entire velocity range. All rigid-model tests and one shell-model test at each nominal scale will be repeated three times to demonstrate reproducibility of data (about 50 tests in all).

In addition to the electronic instrumentation, high-speed motion pictures of the impact process will be taken from below the water surface.

The tests are scheduled for completion in June 1977. *Project Managers: Charles W. Sullivan, John J. Carey, George E. Sliter*

Correction

On page 40 of the article "ATWS—Impact of a Nonproblem" in the March issue of the JOURNAL, the first sentence of the last paragraph should read: "These are both for exceeding the 25-rem two-hour iodine thyroid dose" *not* "These both far exceed the 25-rem two-hour iodine thyroid dose."

R&D Status Report
FOSSIL FUEL AND ADVANCED SYSTEMS DIVISION

Richard E. Balzhiser, Director

NO_x CONTROL TECHNOLOGY

Coal-fired steam generators

A major constraint on the use of pulverized coal for power generation will be emissions of oxides of nitrogen. Relatively minor changes in burner designs and boiler operating procedures (i.e., staged combustion and low excess air) have been applied to satisfy the 0.7 lb/10^6 Btu new-source performance standards for NO_x. Refinements of these procedures will probably be applied in response to the 0.6 lb/10^6 Btu NO_x standards for coal-fired steam generators recently proposed by EPA, although questions regarding furnace tube corrosion and potentially toxic by-products, such as polycyclic organic matter, are as yet unanswered. However, EPA is considering lowering NO_x standards even further: EPA research goals of 200 ppm NO_x in 1980 and 100 ppm in 1985 have been established for pulverized-coal steam generators.

For obvious economic reasons, the emphasis on NO_x control at EPRI has been on the combustion modification method. A $2 million cost-shared contract has been signed with the Babcock & Wilcox Co. (B&W) to develop a low-NO_x combustion process for coal-fired utility boilers. A lower priority has been placed on postcombustion alternatives because of the substantially higher costs involved and the likelihood of major reliability impacts.

Low NO_x combustion process development

The major problem in trying to achieve low NO_x levels from coal is similar to that encountered with sulfur—the nitrogen organically bound within the coal molecules is the source of the emissions. Were this fuel-bound nitrogen not present, such control technologies as wind-box flue gas recirculation and staged combustion would be adequate to control NO_x to very low levels, as evidenced by considerable data from natural gas and residual oil-fired boilers. The fuel-bound nitrogen, however, is unlike its sulfur counterpart in that it does not necessarily result in a solid by-product (scrubber sludge, sulfuric acid, or even elemental sulfur) that somehow must be disposed. There is a considerable amount of data indicating that the fuel nitrogen may be reduced to innocuous molecular nitrogen by properly manipulating the combustion chemistry.

The fundamental requirement to accomplish the conversion of fuel nitrogen to N_2 is through fuel-rich combustion. However, this cannot be accomplished by an extension of current staged-combustion techniques with conventional burners. It requires a completely new burner technology that can provide the proper temperature, time, and stoichiometry for low NO_x. The system must physically isolate the fuel-rich combustion process from the secondary air injection zone, which is required to maintain an overall oxidizing condition in the boiler. One approach is the primary combustion furnace concept proposed by B&W (Figure 1). Pulverized coal is introduced into a conventional B&W dual-register burner with less air than is required for complete combustion. Any resemblance to existing burners ends at this point. The extended length of the combustor provides the necessary residence time to partially oxidize the coal and permit the desirable N_2-producing reactions to occur. Heat removal will also occur along the combustion chamber to avoid slagging. (Note the similarity between this process and gasification.) Secondary air is added at the exit of the primary combustion furnace to bring the combustion products to oxidizing conditions for the balance of their passage through a conventional convective section.

The development of the low-NO_x combustion process will be performed on two scales. The first tests will be at 4 10^6 Btu/h. These tests will evaluate the process variables necessary to accommodate low NO_x while maintaining acceptable combustion characteristics. Heat removal, residence time, and quantity of air in the primary combustion furnace are major parameters to be defined. Due to the small scale, only overall aspects of reliability can be evaluated in this research. Following successful completion of testing at the 4 10^6 Btu/h scale, research will then move to a 50 10^6 Btu/h facility. This research will confirm the NO_x and combustion process variables determined in the earlier work and evaluate material requirements, mechanical design, and longevity. Results of the 50 10^6 Btu/h tests can be extrapolated to typical full-scale utility burner ratings (150–200 10^6 Btu/h).

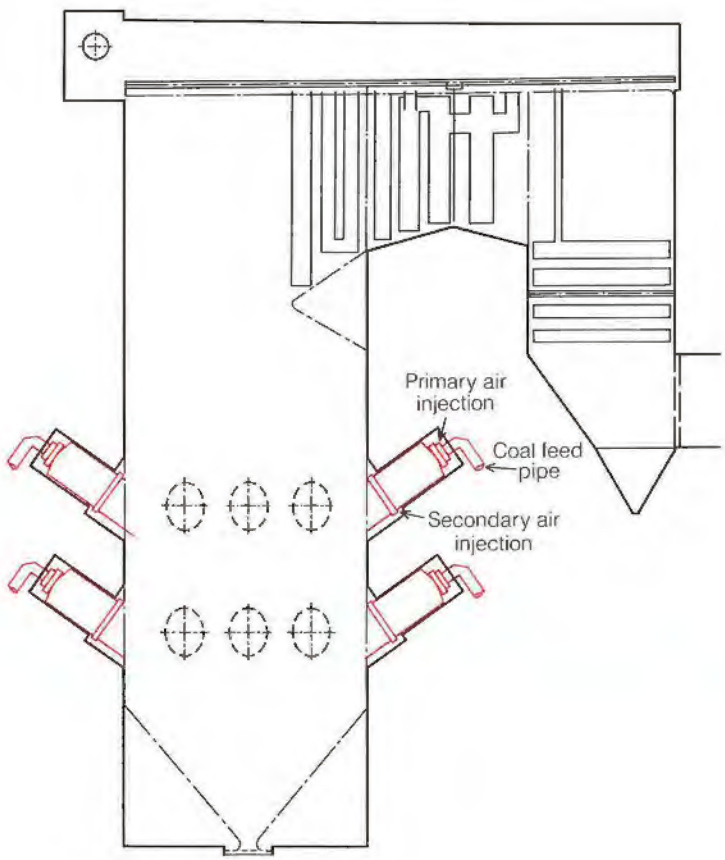
Cost estimates for this technology have been provided by B&W. New unit costs are estimated at under $5/kW and retrofits are projected to be under $20/kW. While these figures must be regarded as preliminary, the attractiveness of the combustion control approach is obvious when one considers that postcombustion control techniques for new units are currently being estimated at $30/kW and up.

Gas turbine–combined-cycle power plants

In addition to the regulations being considered for pulverized-coal power plants, EPA has issued proposed emissions standards for industrial gas turbines. NO_x emissions will be limited to 75 ppm at 15% O_2 for both liquid and gaseous fuels. Emissions regulations for CO and hydrocarbons do not appear likely.

The only means currently available for meeting these standards involve water (or steam) injection into the combustor. Unfortunately, this technique has a capital cost of at least $10–$15/kW and a fuel consumption increase of 2–3%. Increased maintenance costs are also probable, so a system that avoids water injection is

Figure 1 Primary combustion furnace concept as proposed by Babcock & Wilcox Co. The extended combustion permits N_2-producing reactions to occur.



desirable. In conjunction with Solar Division, International Harvester Co., EPRI has undertaken a project to evaluate the feasibility of a low-emission combustor that does not use water or steam, commonly referred to as the dry approach.

There are several ways of controlling NO_x without water injection. All these, however, require that the fuel and air be completely mixed prior to combustion. The most difficult conventional fuel to accommodate is No. 2 distillate because it must be vaporized as well as mixed before combustion occurs. Accordingly, most research has centered on this fuel. The most common premixed combustion method uses high-pressure ($\sim$ 10 atm) and high-temperature ($\sim$ 650°F) combustor inlet air to provide the heat of vaporization of the distillate oil. Figure 2 is a photograph of the combustor tested. The main fuel injection is into the premixing ports. During its passage through the ports, the fuel is evaporated and mixed to a uniform stoichiometry with the airstream. At this point, the fuel-air charge enters the primary zone where combustion occurs. Subsequent secondary and dilution zones are designed, using essentially conventional combustor design principles. Fuel can also be introduced through the precombustor. This provides the capability to independently vary inlet air temperature and also permits added turndown flexibility.

Preliminary results of the emissions performance of the dry combustor have been obtained. Up to about 7-atm combustor pressure, emissions are within proposed EPA standards. However, at the design operating pressure of 10 atm, emissions several times higher than required were observed. The probable cause of the high emissions is incomplete evaporation and mixing of the fuel in the vaporization tubes. One solution to improved fuel vaporization is increased combustor inlet air temperatures. However, increasing the temperature produced autoignition of the fuel-air mixture in the vaporization tubes. Autoignition resulted in failure of the fuel preparation ports.

Development of a dry fix for gas turbine NO_x will require much additional research before a commercially acceptable solution is found. *Project Manager: Donald Teixeira*

CLEAN LIQUIDS FROM COAL: IDEAS AND REALITY

In 1976 two major events put coal liquefaction firmly on the road to commercialization. Groundbreaking ceremonies were held on December 15 on the site of the H-Coal process pilot plant in Catlettsburg, Kentucky (Figure 3). When in operation in 1978, this plant will process 250 ton/d of coal to make an all-distillate synthetic crude oil, or 600 ton/d to produce heavy boiler fuel. This project is being funded by EPRI, ERDA, the Commonwealth of Kentucky, Ashland Oil Co., Mobil Oil Co., Conoco Coal Development Co. (a subsidiary of Continental Oil Co.) and Standard Oil of Indiana.

The second event was the agreement effective the beginning of 1976 between EPRI, Exxon Research and Engineering Co., and ERDA to fund further development of the Exxon Donor Solvent (EDS) process. Based on the current research and development effort, detailed design of a 250-ton/d plant to be located at Baytown, Texas, can begin. This plant is scheduled to be operational by 1980. EPRI support for the Baytown plant was recently approved by the Board of Directors.

Successful completion of these efforts, which are based on different technologies, will provide a basis for proceeding with acceptable technical risk to commercial plants in the mid-1980s.

The major thrust of the Clean Liquid and Solid Fuels Program is the development of processes for the production of liquid fuels

Figure 2 Combustion at 7 atm has been successful in limiting emissions to EPA standards. At 10 atm, however, emissions are much higher than EPA permits.

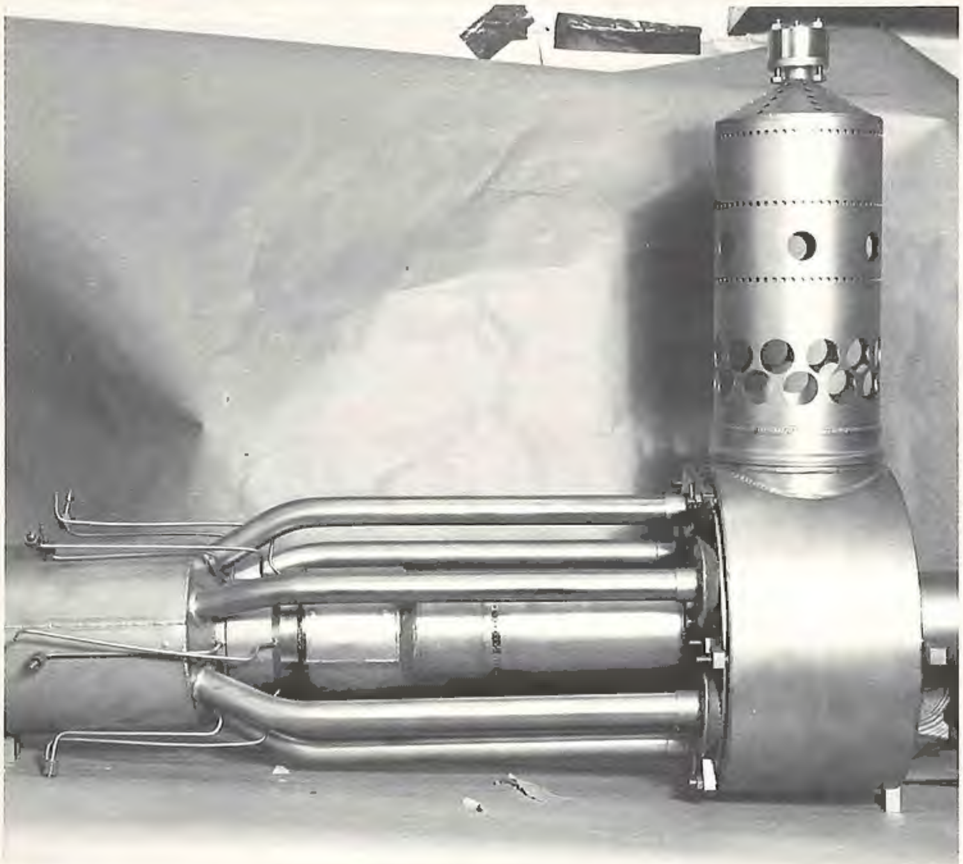


Figure 3 H-Coal pilot plant site at Catlettsburg, Kentucky. Construction is to be completed in 1978.

from coal. One advantage of these fuels is that they can meet any reasonable environmental requirement. Liquid fuels are stable, compatible with present equipment, and transportable. Of primary importance, however, is that their sulfur and nitrogen contents can be varied to satisfy rigorous emission requirements. They can be best used for intermediate and peaking fuels when it is uneconomical to install post-combustion pollution control equipment.

A variety of processes are being developed to produce liquid fuels from coal. Those with the highest yield of liquids, about 3–4 bbl/ton of coal, are based upon hydrogenation methods. Other approaches that yield 1–1.5 bbl/ton of coal are based on pyrolysis, either in the presence of essentially inert gas or hydrogen. A major by-product of pyrolysis is char with a sulfur content that is about the same as the feed coal.

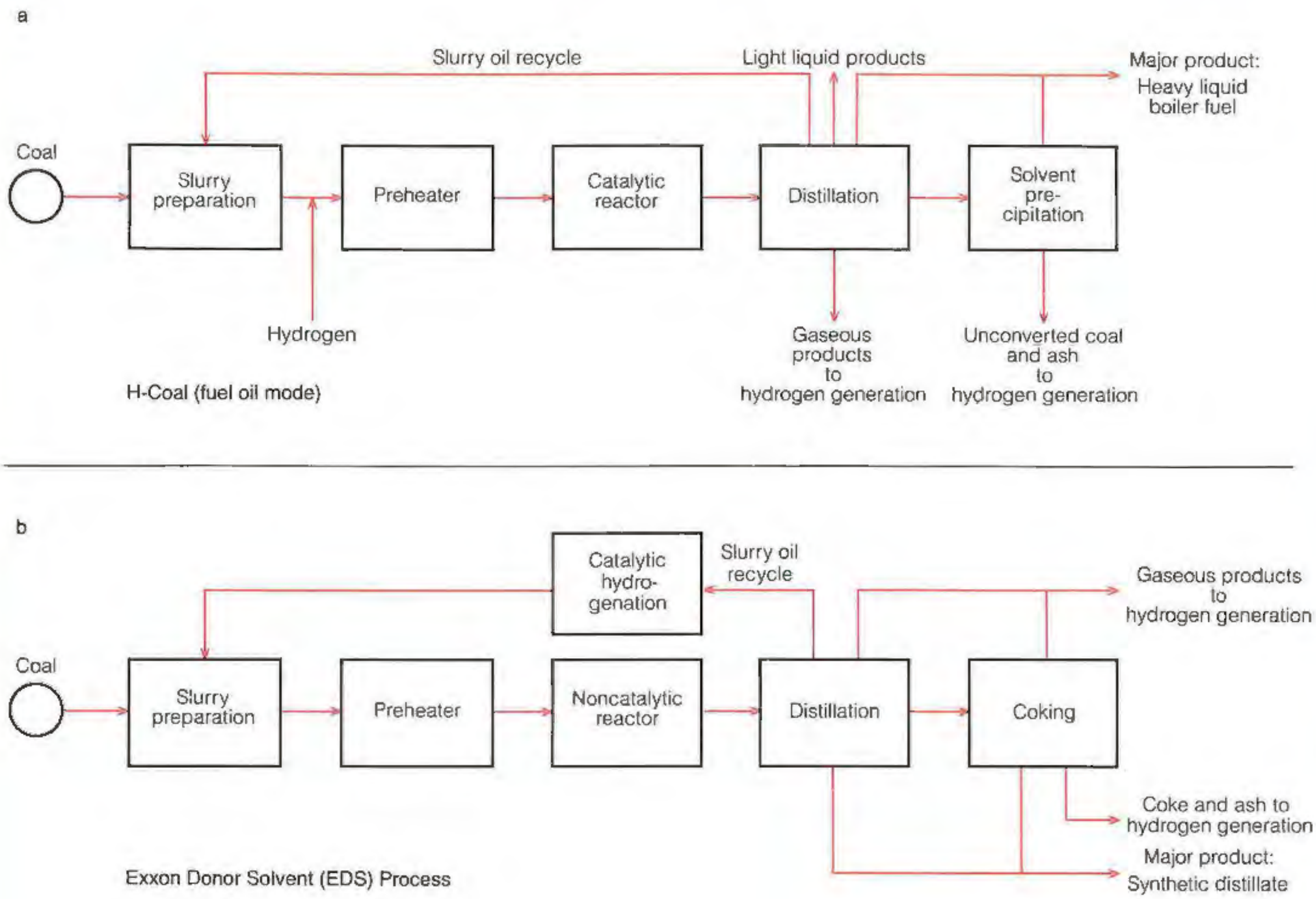
EPRI has chosen to support the further development of two alternative hydrogenation processes. Each is the furthest developed of its type and both offer the best chance of technical and economic success. The H-Coal process is a direct catalytic process: the EDS process is an indirect catalytic process. The terms *direct* and *indirect* refer to whether the coal and the catalyst are in actual contact with each other.

Simplified flow sheets presented in Figure 4 identify key features of each process. In the H-Coal process, coal is slurried with oil recovered from the process downstream of the reaction section, mixed with hydrogen, preheated, and fed to a liquid-phase, fluidized-bed, catalytic reactor in which the coal dissolves.

In the EDS process, coal is slurried with hydrogen-rich distillate oil that has been recovered from the process and hydrogenated in a separate, fixed-bed, catalytic hydrotreater. This slurry is mixed with additional hydrogen, preheated, and fed to an empty liquid-phase, high-pressure reactor in which the coal dissolves. As a result of the different routes, the remainder of each plant is very different; even the operating conditions in the reaction section are different. A qualitative comparison is shown in Table 1.

In both processes, the dissolution of coal results from the rupture of the bonds that tie together its polymeric structure. The fragments of this breakdown react with hydrogen released from the slurrying oil and the hydrogen provided from gasification of a small portion of the products. After reaction, the tendency for the fragments to repolymerize is significantly lessened by the presence of hydrogen and by dilution with

Figure 4 (a) H-Coal process flow sheet shows the direct catalytic liquefaction of coal. The major product is a heavy, low-sulfur, fuel oil substitute. (b) Exxon Donor Solvent process flow sheet shows the indirect catalytic liquefaction of coal. Coal and catalyst are not in direct contact. The catalyst aids in increasing the hydrogen content of the oil used to dissolve the coal. The major product is a distillate fuel oil.



liquids having hydrogen-donating qualities. Additional cracking of these fragments and further reaction with available hydrogen results in the production of lower-boiling products. The role of gaseous hydrogen is primarily to replenish the hydrogen being released from the solvent and to quench cracked fragments, thereby preventing coke formation.

Technical differences

Both processes carry out the coal dissolution step at about the same temperature. In the EDS process, the solvent quality is controlled independently by the operating conditions chosen for the hydrotreating reactor. Therefore, the amount of donable hydrogen in the solvent can be controlled to the level required to obtain the desired yield of product. With the single-reactor H-Coal system, the catalyst serves to simultaneously hydrogenate solvent and hydrocrack heavy products. However, the operating pressure of the single reactor must be higher than in the two-reactor system. On the other hand, the total high-pressure reactor volume is smaller.

In both processes organic sulfur is removed primarily by reaction with hydrogen. Hydrogen is converted to gaseous hydrogen sulfide, which is subsequently removed in the recycle gas purification system. Pyritic sulfur, FeS_2, is converted by reaction with hydrogen to FeS, which is rejected in the solids separation system. The hydrogen sulfide formed is removed in a separate gas purification system. All sulfur that is converted to hydrogen sulfide is essentially quantitatively converted to solid elemental sulfur. The sulfur content of the liquid products is a function of the amount of organic sulfur in the feed coal and the processing conditions selected.

As a consequence of consuming all the hydrogen in a single reactor, the amount of exothermic reaction heat generated in that reactor is higher. This allows a significantly reduced preheater outlet temperature compared to the two-reactor system. Preheating reactor feeds to temperatures closely approaching those in the reactors

Table 1
COMPARISON OF H-COAL AND EDS PROCESSES

	H-Coal	*EDS*
Technical approach	Direct catalytic	Indirect catalytic
Reaction section		
Operating pressure	Higher	Lower
Total high-pressure reactor volume	Lower	Higher
Reactor types	One	Two
Catalyst consumption	Higher	Lower
Catalyst bed	Fluidized, in contact with coal	Fixed, not in contact with coal
Preheater outlet temperature	Lower	Higher
Other considerations		
Product objectives	Low severity—heavy boiler fuel	Distillate oil
	High severity—distillate oil	
Solid separation alternatives	Heavy boiler fuel—solvent	Distillate oil—distillation
	Precipitation or filtration	
	Distillate oil—distillation	
Hydrogen/Fuel gas	Steam methane reforming of light gases	Steam methane reforming of light gases
Generation alternatives	Partial oxidation of precipitation or distillation residue	Fluid-bed coking of distillation residue
	Gasification of filtration residue	Gasification of fluid coke

presents a technical problem in the design of commercial systems. Successful operation must be demonstrated on a large scale.

Eliminating direct contact between coal and the heavy products from coal dissolution as practiced in the EDS process greatly extends useful catalyst life. Catalyst poisons are present in the coal ash and the heaviest products from coal dissolution. Specific poisons include titanium, calcium, sodium, and iron. Heavy liquid products that are absorbed on catalyst surfaces inhibit catalytic activity by blocking pores and preventing the flow of reactants into and out of the catalyst structure.

Using a fluidized catalyst bed in the H-Coal process has advantages and disadvantages. The term *ebullated bed* has been used to describe this fluidization regime, since both upflowing gas and liquid play a role in the fluidization process. Almost all the lifting power comes from the flow of liquids. Gas flow greatly increases turbulence. In this violently agitated system, the heat of reaction is absorbed by mixing with feed to the reactor, and there is no pressure drop because of the absence of flow restrictions between particles.

Since the expansion of the bed is controlled primarily by liquid flow, large quantities of liquid must be recirculated. The amount of circulation required is a function of the physical properties of the liquid, primarily viscosity and density. These change as a function of reactor conditions, coal type, coal conversion level, and solids concentration in the reactor. Controllability and stability of this system in a large-diameter reactor remain to be demonstrated for a coal liquefaction system. They have been demonstrated in 13-ft-diameter reactors for heavy oil hydrogenation (H-Oil process). With the ebullated-bed reactor system, a small amount of the catalyst inventory (1–2%) is replaced each day. In this way, catalyst activity can be maintained at a desired level.

Utilization of a fixed-bed reactor in the EDS process for hydrotreating distillate oil is a modest extension of present petroleum refining, hydrocracking, and hydrotreating experience. The amount of hydrogen consumed and the concomitant high heat release place this process at the upper end of the spectrum of commercial practice. Special relationships to determine the proper amount of catalyst present between quench points may have to be developed for this system.

Product objectives can be varied with the H-Coal process primarily by varying coal throughput. With high coal rates and therefore lower hydrogen production, the product is similar to heavy boiler fuel. Filtration, or more likely solvent precipitation, will be used to separate solids. At lower throughput rates and higher hydrogen requirements, the product is an all-distillate syncrude. Solids separation can be accomplished by vacuum distillation. The residue from this distillation is fed to a partial oxidation unit to generate hydrogen. With the EDS process, solids separation is accomplished by vacuum distillation. The residue is sent to a Flexicoker. In the first stage of that unit, additional liquid is recovered by coking of the residue. Coke is then fed to an air-blown gasifier to produce fuel gas, which then provides process heat.

Current status

H-Coal has been operated on a 3-ton/d scale and EDS process on a 1-ton/d scale. This has shown that these processes work, using laboratory equipment. However, although excellent work has been performed, these routes to clean boiler fuel from coal are a long way from commercial reality. The economic attractiveness of a capital-intensive facility depends very strongly on its availability. Present estimates of the capital and operating costs of these two processes are about the same. It is necessary to proceed to the 250–600 ton/d pilot plant scale to demonstrate the technical feasibility of each key step at a larger scale. This will allow a decision to be made on the suitability of each process for wide-scale commercialization. With a better engineering basis, management can evaluate the financial incentives and technical risks involved in establishing an industry that will provide clean fuels from coal for power plants that will be operating in the 1990s. Without the support of these projects by EPRI and the U.S. electric power industry, they would simply be laboratory ideas instead of alternative technologies with good potential for commercial application. The two events described at the beginning must be regarded as major accomplishments. *Program Manager: Ronald Wolk*

FUSION POWER RESEARCH

For an early and successful commercialization of fusion power plants, utility operational requirements must be continually compared with the projected capability and performance of fusion power systems being developed by the U.S. government. This comparison can be accomplished through a series of trade studies based on a parametric systems analysis of conceptual fusion reactor designs. Such analysis will result in concept and/or requirement changes and must be continued as a feedback process during the entire development time to ensure a fusion power plant of maximum usefulness to the utility industry.

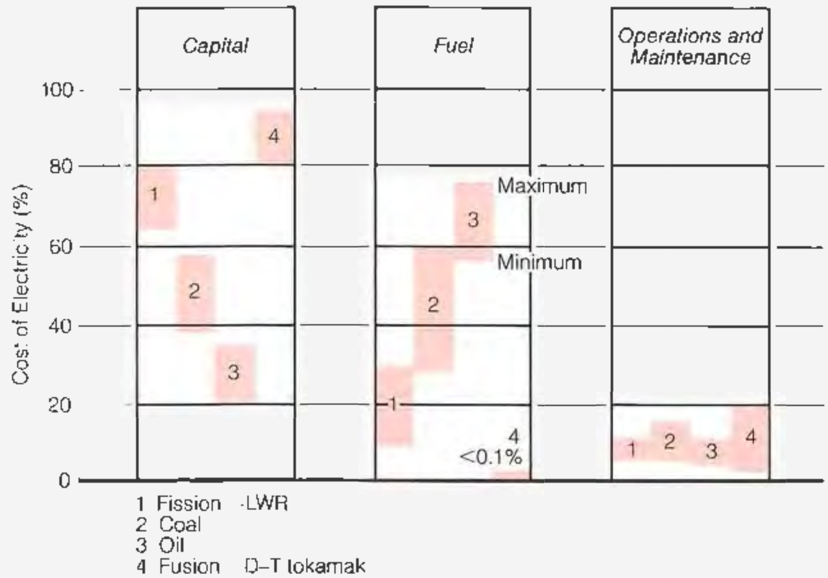
Such an approach is routinely used in complex, long-range military and space programs. However, for a complex civilian technology such as fusion power, in which the eventual user and the developer are separate entities, a special effort is required to ensure a good feedback process for comparing requirements and system capability.

EPRI is developing the methodology and initial tools for such an approach to fusion power. At this early stage only the broad critical elements that affect utility requirements need to be considered. The relationship that determines the cost of electricity generated by a fusion power system tends to be dominated by the capital investment (Figure 5) and the degree of plant availability. The other factors, annual operating cost and fuel costs, tend to be small by comparison. Therefore, a study was initiated to define the impact of first-wall/blanket design concepts and parameters on fusion plant capital investment and availability (RP472). In addition, because of the influence of radiation-induced structural damage, a strong emphasis was placed on developing the tools and techniques for predicting first-wall/blanket life. The project is funded jointly by EPRI and the McDonnell Douglas Corp.

The study first defined nine conceptual design issues involved in establishing capital cost and availability levels:

- Plasma confinement concept
- Subsystem definition
- Materials
- Wall loading
- Operating cycle time
- Power capacity
- Wall life
- Maintainability
- Reliability

Figure 5 The cost of electricity generated by a fusion power system is dominated by the capital investment. The capital costs may be reduced by alternative fusion reactor concepts that provide simpler geometries with more economic construction techniques and permit higher power densities and smaller modular units.



The first three issues are intimately related to the available technological options for fusion and hence have different relative risks associated with any choice; for example, the selection of the plasma confinement concept, the subsystem methods of plasma heating, and the choice of structural materials for the first wall.

A report of these studies has just been published (EPRI ER-386). It is through such parametric studies that we can ascertain that utility objectives for fusion power systems are being met. These studies also allow us to identify problem areas and indicate where fusion alternatives should be explored.

Fusion options

By its very nature and because of its early state of development, fusion power has many available options for overcoming or circumventing its problems. EPRI is assessing this option space to seek R&D directions that could lead to systems better suited to utility requirements. The following examples illustrate how new options obtained through design ingenuity, choice of materials, and choice of fusion fuel cycle could impact the fusion reactor first-wall/blanket system.

Design Ingenuity In fusion, the volume in which the neutrons are generated is completely separated from the volume in which the energy is extracted. Fusion neutrons are generated in a plasma and then interact with materials located a considerable distance away. This characteristic of fusion systems may be used to reduce the effects of radiation damage in a way not available to fission systems because radiation damage effects are temperature-sensitive. Thus, fusion reactors may be tailored so that materials that receive the highest neutron fluence operate at a temperature where longer material lifetimes are achieved.

Such temperature tailoring has been applied by the University of Wisconsin as part of an EPRI study on inertial confinement fusion reactors (RP237). Consideration of plant efficiency favors a high operating temperature for the first wall and blanket, whereas structure life considerations favor a lower temperature. However, since only approximately 20% of the energy is deposited in the first wall, total plant efficiencies can be maintained at reasonable levels with low first-wall temperatures. For example, the University of Wisconsin has developed a blanket design that uses flowing Li_2O particles as the blanket heat transport medium, while separately using boiling water cooling for a first wall. This offers the possibility of sharply reducing the irradiation temperature in the first wall to the 250–300°C range.

Although it is well known that radiation damage effects are temperature dependent, at this time it is difficult to pick the temperature that will provide the longest life. For example, for 316 stainless steel, swelling is greatly reduced at 250–300°C compared with 500°C, but embrittlement by matrix hardening is greater at 250–300°C than at 500°C. To determine the temperature for longest life requires knowledge of the actual failure mode and, consequently, the material properties that control this failure mode. Operating the first wall at a lower temperature can provide other advantages, such as improved material strength properties, corrosion resistance, and thermal creep resistance. Taking all these factors into account, the concept of temperature tailoring may provide a significant increase in first-wall life. Such a life increase will substantially increase plant availability and thereby reduce the cost of fusion power.

Low-Activation Structural Materials for Fusion Reactors An especially important issue, implicit in the first-wall/blanket systems analysis (RP472), is that operation of planned fusion reactors with deuterium-tritium (D–T) fuel will cause all the structural metals already chosen for these systems to become seriously radioactive. Since these materials will be replaced periodically because of thermomechanical wear-out and radiation damage, the difficulties of dealing with radioactivity could significantly affect plant availability and the eventual cost of electricity. Among the factors that will depend on the activation levels, biological hazards, and decay rates of transmutation isotopes are:

- Reactor repair and maintenance procedures
- Storage requirements for activated components that are removed from reactors
- Personnel safety
- Environmental (siting) restrictions

These factors will, in turn, significantly influence the societal acceptance, as well as the cost, of fusion power reactors.

One way induced radioactivity in fusion can be reduced is to seek materials that do not become very radioactive in the 14-MeV neutron environment or that form radioactive daughters that decay very rapidly. Fortunately, there are a number of elements, such as aluminum, carbon, magnesium, oxygen, silicon, beryllium, titanium, vanadium, and certain alloys and compounds of these elements, that have much more favorable activation/decay characteristics than do stainless steels, nickel alloys, or the so-called refractory metals. In general, however, the metals and alloys that have the most suitable properties for constructing large, high-temperature devices become the most radioactive, and the materials that have low activation levels present other kinds of structural limitations (such as inadequate temperature resistance, susceptibility to radiation damage, brittleness, and incompatibility with proposed coolants).

To help assess the feasibility of using low-activation materials extensively in fusion machines, an EPRI workshop was held in February 1976 (ER-328-SR). Representatives from utilities, architect-engineering firms, manufacturers, metals producers, and national laboratories attended. The 30 specialists concurred on the need for a coordinated research effort on the activation problem and identified two general directions for R&D. Both involve determining the capability of materials to implement low-activation designs, but differ as to the proper trade-offs that will be required. One path chooses the benefits of designing with ductile metals and thereby accepts a modest level of activation; the other chooses the lowest possible induced radioactivity, which is obtainable only with ceramics, and must confront the difficulties of incorporating brittle substances into load-bearing structures.

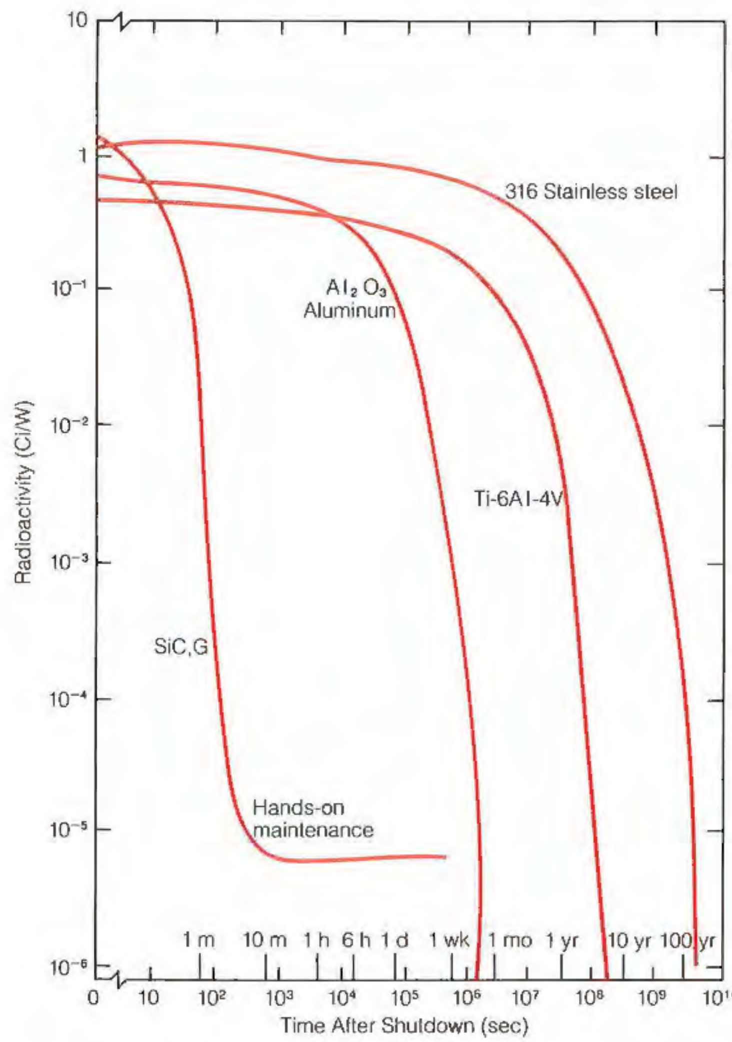
Aluminum, magnesium, and beryllium are low-activation structural metals, all having limited temperature resistance. Magnesium has no known advantage over aluminum, has inferior corrosion resistance, and is less widely used and characterized. Beryllium is expensive, is in short supply, and is difficult to fabricate into complex structures. Therefore, aluminum was selected as the most likely candidate from this group, especially inasmuch as aluminum/aluminum-oxide composites offer the possibility of much higher strengths and temperature resistance than do purely metallic aluminum alloys. Titanium and vanadium have reasonable temperature capabilities, but vanadium has no industrial base and is very sensitive to environmental degradation. Thus, although relatively little is known about the neutronic properties of titanium, it was chosen for further study on the basis of a preliminary assessment in RP472. A project is being initiated to address the following important unresolved issues associated with using low-activity alloys for structures in fusion reactor environments: the effects of transmutation helium and hydrogen on the mechanical properties of high-purity aluminum and titanium alloys; the probability of finding high-purity aluminum alloys with adequate corrosion resistance to high-temperature water; the evaluation of swelling behavior, mechanical and neutronic properties, and coolant compatibility of titanium alloys.

Ceramics involve even greater difficulties of utilization (and conversely, greater promise) than do metals for first-wall/blanket systems. Lower atomic number substances, such as graphite and silicon carbide, are particularly attractive from the standpoint of low activation; compared with even the "best" metals, residual radioactivity would be decreased by many orders of magnitude following exposure to fusion environments, as shown by Figure 6. In addition to their advantages in terms of activation, these low-Z materials have been widely proposed for plasma-facing applications because they offer the potential for reducing the effects of plasma contamination from sputtering and erosion processes. These advantages, however, may be difficult to realize in practical systems, since ceramics are brittle. A necessary first step is to identify those techniques and methods that must be invoked in order to ensure satisfactory ceramic components (in terms of structural reliability and of function) in spite of intrinsic brittleness.

As a result of the foregoing considerations, a modest scoping project has been undertaken to assess the feasibility of constructing a fusion reactor with ceramic materials that have very low neutron activations or very rapid afterheat decay (RP992). The work is being conducted in three broad phases:

- The evaluation, particularly from a mechanical design standpoint, of structural ceramics envisioned for first-wall and blanket regions of fusion reactors
- The elucidation of initial design concepts that can form a basic framework for the practical application of ceramics in fusion reactors
- As a result of the first two activities, the development of a road map, or plan of work,

Figure 6 Operation of fusion power reactors with deuterium-tritium fuel will cause the structural materials to become radioactive. This induced radioactivity can be significantly reduced by choosing materials that do not become very radioactive in the 14-MeV neutron environment, or which form radioactive daughters that decay very rapidly. The figure shows that the induced structural radioactivity in a D–T fusion reactor after two years' operation at 5000 MWt can be reduced by as much as seven orders of magnitude and might even permit hands-on maintenance.



that will lay out the R&D steps necessary to develop ceramics for fusion reactor applications

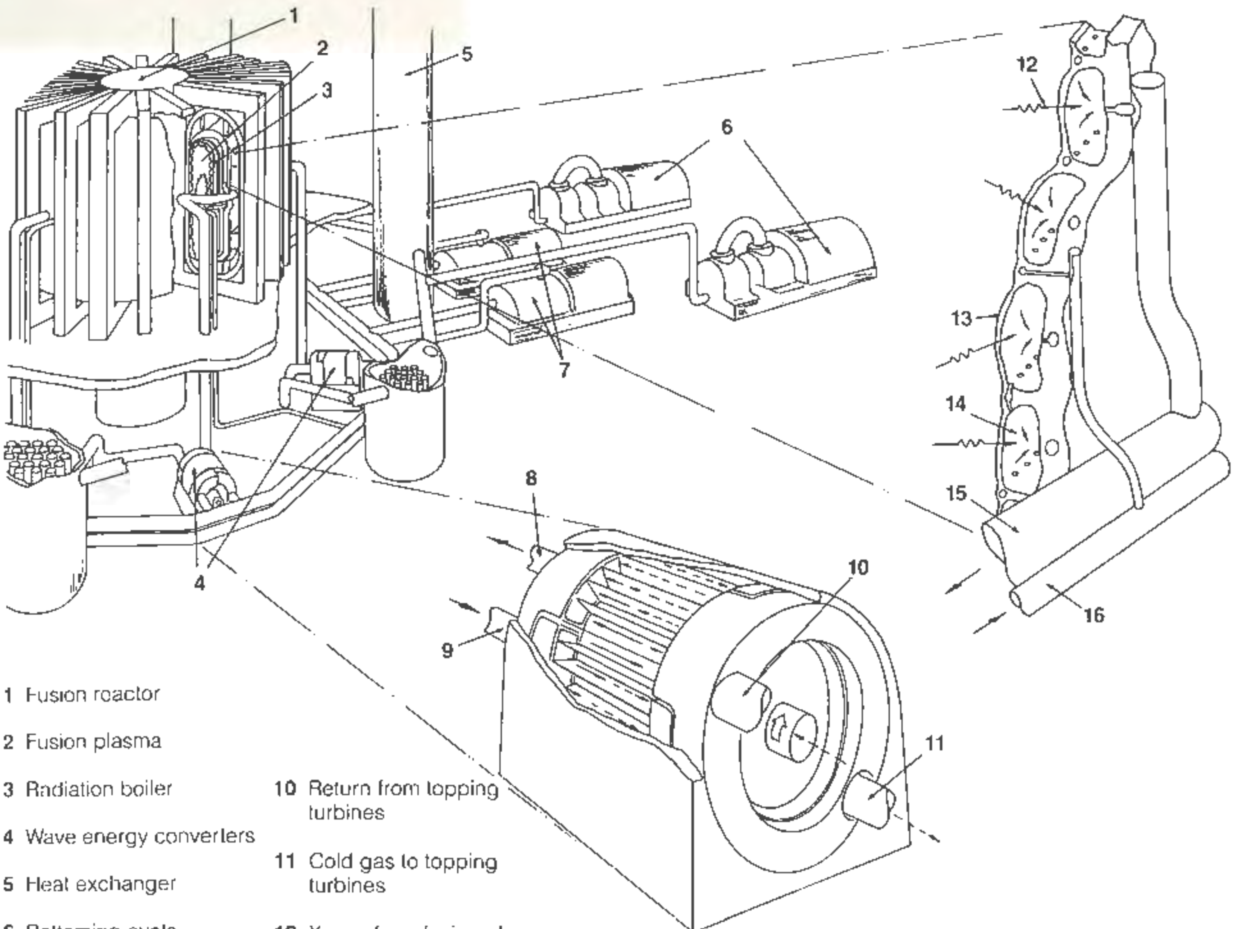
A major goal for these efforts is their use as a vehicle for identifying key limiting problems and the potential payoff (in terms of improved operational limits) that may be associated with a successful solution.

Advanced Fusion Fuel Cycles The present national fusion program is progressing toward the goal of electric fusion power essentially along the path of one fusion fuel, D–T. This effectively limits the technology development to a 14-MeV neutron-producing fusion reactor system and imposes the complications of tritium breeding, neutron activation, remote handling, and complex blanket design. Although no future energy source can eliminate all concerns, there are alternative fusion paths that may lead to simplified and more acceptable technology than using D–T fuels, although they require the achievement of more difficult plasma physics conditions. Two paths are being explored in EPRI-funded projects. One involves D–D and D–^{3}He fuels, using conventional magnetic confinement configurations such as tokamaks and mirrors (RP645). The objective of this study in its second year is to evaluate the merits of the various advanced-fuel reactor systems compared with a D–T system. The project involves three principal contractors, the University of Illinois, Brookhaven National Laboratory, and Lawrence Livermore Laboratory. So far, studies show viable designs for D–D and D–^{3}He tokamaks, using the recent improved estimates for fuel confinement in tokamaks. If these encouraging results prove feasible, the application of new fusion fuels can greatly simplify the ultimate reactor technology—eliminating tritium breeding, simplifying the energy extraction, increasing the overall efficiency, and improving potential for direct energy conversion. In addition, evaluations of field-reversed mirror fusion reactors using D–D and D–^{3}He show promise of small unit size and simplicity, offering a technological option to tokamaks.

The other approach to fusion involves "neutronless" fusion fuels that have more severe fuel core requirements (higher temperature and better fuel confinement) but produce essentially no neutrons. Much of the power output exits as electromagnetic radiators (X rays), and the rest, as charged particles. These conditions lead to the possibility of very high efficiency of energy conversion. The most likely fusion reaction of this sort is

$$p + {}^{11}B \longrightarrow 3\,{}^4He + 8.7\ MeV$$

although there are others. The outstanding disadvantages of these reactions are that significant fuel burn rates are obtained only at temperatures above 150 keV, and the fuels require very favorable plasma confinement. These objections have traditionally minimized interest in such reactors. However, in the present climate of environmental and complex technology concerns, the advantages of such neutronless reactions have created interest in carefully evaluating the possibilities of such reactions. Among some



1 Fusion reactor

2 Fusion plasma

3 Radiation boiler

4 Wave energy converters

5 Heat exchanger

6 Bottoming cycle turbines

7 Topping cycle turbines

8 Exhaust to heat exchangers

9 Hot gas from radiation boiler

10 Return from topping turbines

11 Cold gas to topping turbines

12 X rays from fusion plasma

13 Low-Z first wall

14 High-Z working fluid

15 Hot gas to wave energy converters

16 Return from heat exchanger

Advanced Fuel Fusion Reactors

Advanced fuel fusion reactors based on deuterium-helium or proton-boron mixtures release most of their energy as hard X-ray radiation or charged particles and, consequently, open the possibility of the so-called neutron-free reactor. All such reactions proposed to date have limited cross sections and require very favorable confinement schemes.

Coupling such an advanced fuel with a more efficient energy conversion concept is almost essential if such advanced reactors are to be realized. The concept shown here accomplishes this requirement by introducing a radiation boiler in which the X rays are absorbed in a high-Z working fluid that is separated from the plasma by a low-Z X-ray transparent solid wall and a device called an energy converter, which couples the turbines to the high-temperature gases.

The high-Z working fluid inside the radiation boiler absorbs the X-ray energy at very high temperatures (about 3000K). The working fluid temperatures may be too high for direct use in turbine generators. Consequently, a wave energy converter is interposed into the electricity-generating cycle. The converter is used to gas-dynamically transfer the enthalpy of the high-temperature fluid to a cooler working fluid. Acoustic impedance matching between the two fluids allows highly efficient energy transfer (e.g., 85–90%) with the advantage that the entire cycle efficiency can be characterized by the Carnot efficiency of the high temperature of the boiler working fluid, while the cold working fluid allows the device to be coupled to a conventional turbine generator. Overall energy conversion cycle efficiencies of better than 60% can be calculated for advanced fuel fusion reactors that use the radiation boiler-wave energy converter concept.

of the specific advantages for the utility industry are:

- Substantial reduction of induced radioactivity due to neutrons will reduce nuclear issues drastically in the public eye.
- The fuels are inexhaustible, cheap, and presently available. The amount needed is small compared with the quantity now used commercially.
- Accessibility and simplicity of the preliminary reactor concept using these fuels should improve performance of a future fusion power station. Technical advantages for manufacturers and utilities include drastic modification to the first wall, changing its requirements completely. This is very important because the first-wall/blanket conditions in a D–T reactor have created severe problems in the development of fusion reactor designs. In the neutronless fusion fuel, the first walls connected to external cooling systems can be designed with much more confidence.
- The complex blanket is virtually eliminated and is replaced by much thinner X-ray-absorbing plates and heat transfer media.
- The structural integrity and life appear to be much improved.
- The preliminary examinations so far indicate the fusion core and boiler would be more accessible, permitting different methods of fuel injection and heating.
- The production of fusion energy in the form of electromagnetic radiation presents opportunities to achieve exceptional efficiency of conversion and use.

A preliminary examination of one reactor concept using $p-{}^{11}B$ is in progress at TRW. This work was stimulated by an EPRI-sponsored assessment effort by Professor John Dawson of the University of California at Los Angeles. It embodies a fusion reactor concept that uses floating magnetic multipoles to achieve efficient fuel containment and to minimize the internal magnetic field. This latter requirement is important because of the severe losses incurred at high fuel temperatures due to synchrotron radiation from the fuel in a strong magnetic field. So far the preliminary results show that a driven system producing 100 MW at an ion temperature of 250 keV, electron temperature of 130 keV, can be sustained with neutral beam heating. Energy is extracted by X rays through a thin Be or Al wall into a high-Z gas, which then can be converted at high efficiency (55–65%) into electricity, or by mixing the high-Z gas with water. The high temperature obtained might be used to break water into H_2 and O_2 for synthetic fuel production. The use of such energy convertors for advanced fuels is being studied at Mathematical Sciences Northwest, Inc., under a recent addition to RP645. *Program Manager: William Gough*

OPEN-CYCLE MHD

Top attention is being given to open-cycle magnetohydrodynamics (OCMHD) as a promising concept for efficient power generation from coal. Preliminary economic comparisons of OCMHD with competing technologies support this position. Over the past few years, national funding for MHD research has made possible extensive investigation of several limiting technical issues and significant advances have resulted. While a number of key technical-economic issues remain to be resolved, these recent results have considerably strengthened the basis for a comprehensive development program for OCMHD technology.

Competitive economics

The recently completed, federally sponsored study on energy conversion alternatives provided a comparison of a number of advanced options for baseload power generation from coal or coal-derived fuels (*1*). Conceptual plant designs were developed and analyzed on economic competitiveness in fixed plant capacity factor (65%), fuel prices, and other assumptions (Figure 7). OCMHD appears to be competitive with the best alternatives in regard to both energy conversion efficiency and cost of electricity. This study was only a preliminary comparison, since it did not account for various important aspects of realistic utility situations. EPRI and the federal government are currently performing more comprehensive studies. However, at this point OCMHD does appear to be an important candidate for advanced power generation from coal.

Technical progress

The major technical issues and the extent of recent progress are shown in Figure 8. The block diagram represents the major subsystems of the most commonly envisioned type of coal-fired OCMHD power plant. This configuration consists of an OCMHD "topping" cycle and a steam "bottoming" cycle.

As indicated by the bold outlines in the diagram, four major segments of the projected MHD plant encompass limiting technical issues. The combustor, the generator, and the associated power conditioning and control equipment, viewed as closely interrelated units, represent one such segment of the OCMHD plant. The superconducting magnet system required for the MHD generator has presented limiting technical issues in fabrication and assembly. The seed recovery and reprocessing subsystem, intended to recover the potassium seed material injected into the flow to increase the electrical conductivity of the combustion gases, represents the third area of major uncertainty. The fourth area of major concern has been the high-temperature air preheaters, which would use the exhaust of the MHD generator to preheat the combustion air to very high temperatures (above 2000°F). The other major subsystems shown in Figure 8 appear to present no limiting technical issues at this point.

Encouraging advances have been made in the development of the air preheaters that are envisioned as being similar to blast furnace heaters, using a series of ceramic beds that alternately cool the exhaust gases from the generator and heat the air going to the combustor. Since the coal combustion products will contain some amount of slag and potassium seed material (present as potassium sulfate), these heaters could be subject to severe corrosion. However, recent tests (*2*) indicate that commercially available blast furnace heater materials will be capable of long-life service while providing preheat temperatures up to approximately 2500°F, a temperature sufficient for the needs of OCMHD systems. Also, a backup position has been established by the successful demonstration of an alternate heater configuration, which would be fired by a separate gas stream instead of the MHD exhaust gases.

Superconducting magnets for baseload OCMHD power plants present a variety of development problems. However, a large, high-field superconducting magnet has been successfully tested in Japan. Also, experience over the last decade with large bubble chamber magnets in the U.S. has provided overall confidence in the ability of U.S. magnet manufacturers to deliver the required magnets (*3*).

Considering the MHD generator itself, tremendous progress has been made over the last few years in understanding the processes involved in the operation of coal-fired and other generators. Recently, Soviet investigators operated a channel at the highest power output (slightly over 20 MWe) ever achieved by their U-25 pilot plant, and the actual power output achieved by the

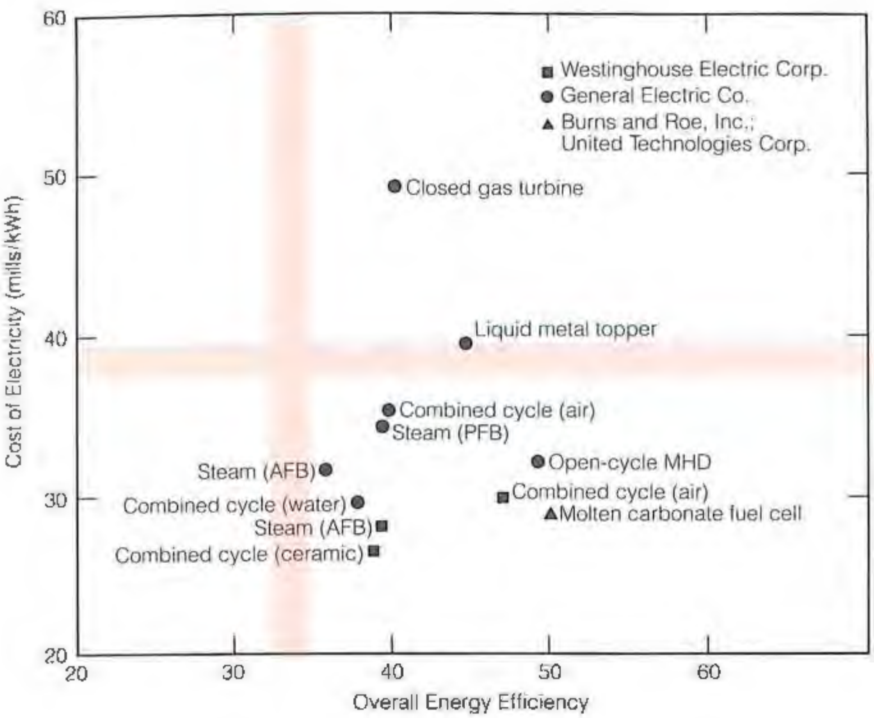


Figure 7 A comparison of Phase 2 results presented by NASA-Lewis Research Center at the ECAS Conceptual Design Review, October 1976. Shaded areas indicate cost and efficiency ranges of conventional steam plants with scrubbers. Most of the systems under study operate both at lower cost and at higher efficiency.

generator was almost exactly the value predicted by theory. In addition, continuous generator operation for durations of over 100 hours has been achieved, using both clean-fuel generators and combustion products containing coal ash. More important, investigators have developed a much better understanding of the material degradation processes occurring in MHD generators (*4*), and promising approaches to the solution of these problems are being tested.

Since MHD generators represent a small fraction of OCMHD plant costs, a generator lifetime of a few thousand hours could be acceptable, depending on the plant downtime required for replacement of the channel. Such lifetimes appear to be within reach.

The power conditioning and control (PC&C) system has been recognized as an important aspect of the development of durable MHD generators (*5*). No advances in PC&C technology are required to produce viable equipment for MHD power plants, but a clear understanding of the interactive design and operation of the generator and PC&C system will be required. Efforts that address this issue are under way.

Coal combustors for OCMHD systems present a number of difficult technical issues. However, recent laboratory tests and experience with related problems in other fields give confidence that these issues can be resolved successfully.

Another area still presenting unresolved technical issues is that of seed recovery and reprocessing. Large amounts of seed material could be lost by absorption in the coal slag present in coal-fired MHD systems. Current plant designs are based on the use of cyclone combustors to extract a large fraction of the slag upstream, thereby limiting possible seed loss. In addition, a number of designs of seed recovery and reprocessing systems have been developed. Although these designs remain supported only by laboratory tests, recent results are encouraging (*6*).

In summary, potentially limiting technical issues associated with superconducting magnets and high-temperature air preheaters have been resolved. Definite progress has been made in the development of combustor-generator-PC&C subsystem combinations to provide adequate performance and durability. Seed recovery and regeneration subsystem designs, while involving a number of uncertainties, are supported by laboratory tests.

Demonstration or commercialization?

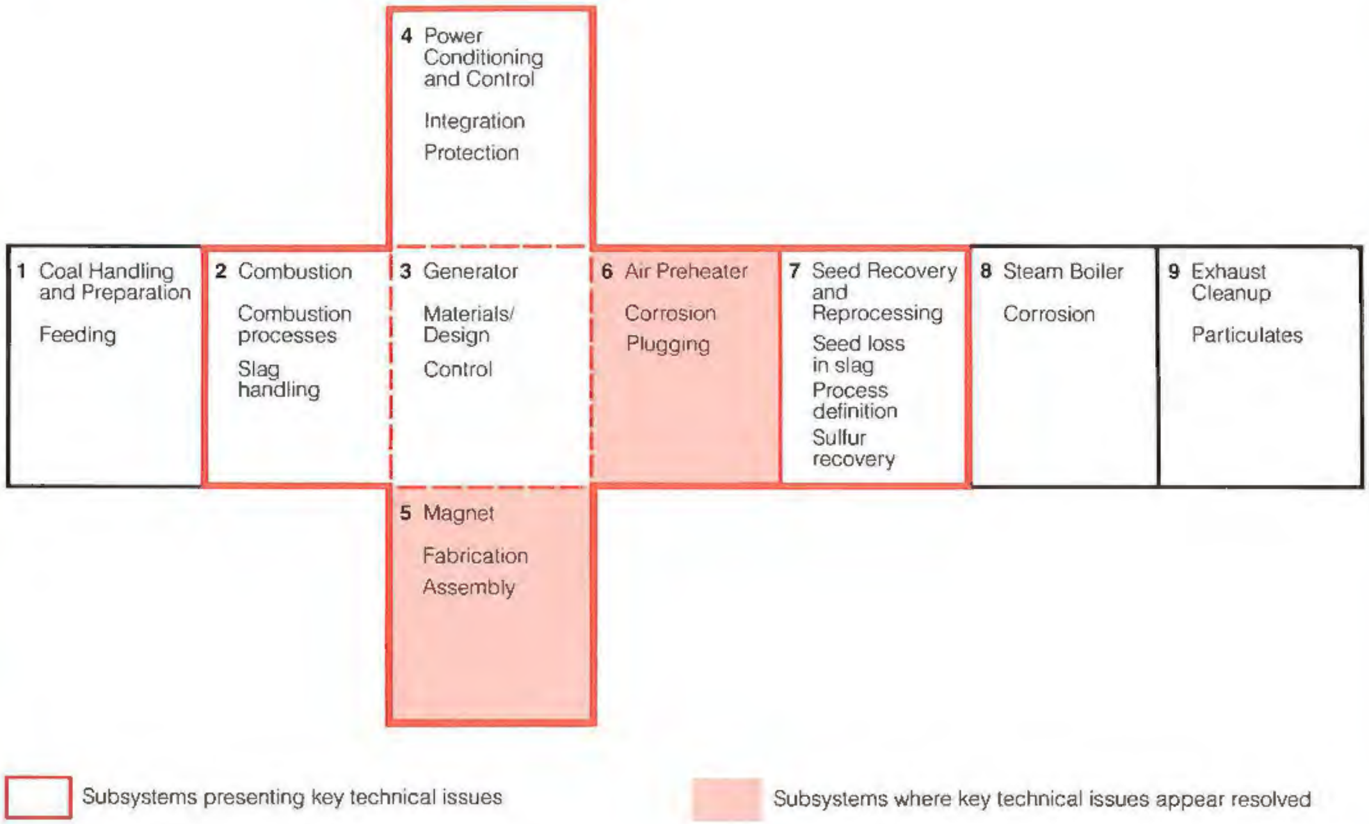
With increasing confidence in the ability of MHD investigators to successfully resolve the remaining technical issues, it is important to ensure that the program is structured and funded to achieve the most effective transition to commercial status. A number of important questions must be addressed. How soon can MHD technology be available to the electric power industry, based on the current national program? Can this schedule be improved? Can the probability of successful development be improved?

Effective transition to commercial status will require the new MHD industry to be involved as a major partner in the demonstration plant. The intention of equipment vendors to offer warranted equipment for sale, pending successful demonstration, should be secure. The customers for the technology, the utilities themselves, should have demonstrated their readiness to accept the technology. The demonstration plant should verify the engineering techniques expected to be employed in the design, installation, and operation of full-scale, operational OCMHD power plants.

With these objectives in mind, we might structure an R&D program similar to that outlined in EPRI SR-12 (*7*). This program begins with comprehensive development efforts for the major subsystems shown in Figure 8 and peripheral equipment. This effort should investigate all important processes involved in the operation of each subsystem, resulting in appropriate performance criteria. These tests should use equipment of the smallest useful scale so that the difficulty and time required for experiments at this stage are minimized, without neglecting important scale-related effects. Multiple facilities should be used where appropriate to increase testing capability. Such an effort would be similar to the subsystem development effort currently under way. However, the current national OCMHD program lacks the funding necessary to address all key issues comprehensively. Consequently, a number of subsystem issues important to the success of the technology are not being addressed to the extent necessary to support future proof tests at pilot scale or to identify problems that could preclude the technology's viability.

The current approach, instead, emphasizes the development of coal-fired combustors and generators with the associated

Figure 8 Coal-fired OCMHD power generation; major subsystems, technical issues, and progress.



Recent Progress

1 Requirements shown to be similar to those of other coal technologies.

2 Small MHD coal combustors operated satisfactorily.

3 Design criteria for slagging and nonslagging walls defined.
Wall degradation mechanisms identified and characterized.
Need for local power flow control identified.
Durability of generators improved.
Performance predictions verified at 20-MWe scale (USSR).

4 Need for integrated development with generator identified.
Present technology shown to be adequate.

5 Superconductor welding techniques for large test facilities demonstrated.
Confidence in engineering based on large bubble chamber magnets.

6 Separately fired heater demonstrated successfully.
Commercially available materials shown adequate for directly fired heaters.

7 Small-scale tests indicate high level of seed/sulfur recovery possible.

PC&C equipment. The engineering of high-temperature air preheaters, the seed recovery-reprocessing system, superconducting magnets, and other subsystems lags behind the work on combustors and generators. Current plans do not address the testing of prototype seed recovery and reprocessing equipment until the pilot plant stage of the current program. Accordingly, some avoidable risks will remain unresolved until the initiation of expensive pilot-scale testing. The currently planned program would proceed from pilot-scale tests to the installation and operation of a government-sponsored, commercial-scale, demonstration plant, currently set to have a capacity of 500 MWe or more. Under this program, the first commercial plants might be expected to enter service only after the year 2000.

To summarize, the commercialization-oriented approach places increased emphasis and funding on subsystem development in multiple small-scale facilities. This would reduce risk and perhaps investment in the later, more expensive stages of the effort. This approach aims at major industrial participation in the demonstration, thereby accelerating the commercialization step and the overall time schedule. Implementing such changes to the current program would require increases in funding over current projections for the next several years. However, the result could be earlier realization of the potential benefits of OCMHD technology.

EPRI's role

EPRI's unique position in relation to the utilities, the government, and the research community affords an opportunity to make a significant contribution to the OCMHD effort with little financial investment. EPRI's current and anticipated role in the development and commercialization of OCMHD power generation comprises three main types of involvement:

- Market assessment and plant design evaluation
- Hardware R&D assessment and/or assistance
- Development-commercialization catalyst

The first area involves continuing assessment of the potential market for OCMHD technology, coupled with the evaluation of reference plant designs in relation to this market. The objectives of this effort are to evaluate on a continuing basis the relative importance of OCMHD development, the potential impact of the technology on the electric utility industry, and the choice of preferred reference plant designs reflecting the needs of the industry. These questions are being addressed directly by EPRI research projects now under way.

The second area of EPRI involvement in the OCMHD program concerns the continuing assessment and support of the nationwide hardware development effort. This activity provides the important capability of independent evaluation of the technical direction of the national program, in addition to an opportunity to assist the hardware development effort. Since EPRI's funding for MHD research constitutes a small fraction of the required support, the research emphasizes technical issues basic to the feasibility of OCMHD power generation. Research on processes, rather than hardware development, is emphasized.

The processes associated with the presence of coal slag in OCMHD systems have been identified as a central issue, and consequently, EPRI's laboratory research projects on OCMHD are addressing this issue broadly. These projects are investigating the behavior of slag in the MHD channel flow stream, the electrochemical and electrodynamic processes involved in current transport through slag layers, and the development of advanced diagnostic techniques and equipment for use in these process investigations and tests of MHD hardware. A recently initiated project will test a flexible PC&C system with an MHD generator supplied by ERDA to assess the processes involved in the control of power flow in the generator, emphasizing the role of slag layers and the control of electrochemical processes occurring at the generator walls.

Setting constraints on the design and operation of the generator-PC&C subsystem to allow for the presence of slag layers could have important effects on the operating regime of other plant susbystems. For example, the requirements for handling slag in the generator might directly affect design requirements for the combustor, the high-temperature air preheaters, and the seed recovery and regeneration system. Thus the EPRI-sponsored projects on slag effects provide a useful basis for evaluation of the remainder of the hardware development effort, while producing information applicable to a wide variety of equipment designs.

The third aspect of EPRI's role in the OCMHD program is to develop a coordinating position in the commercialization of the technology. One objective of this effort is to foster effective technical information exchange within the MHD community itself. Toward this end, EPRI is moving to establish a number of groups of technical specialists who would address key areas of the MHD development program. These small groups of investigators would meet on a continuing basis to assess research results and recommend additional research efforts.

Another aspect of this role as a development-commercialization catalyst is to provide continuing communication between the MHD community and the electric utility industry, both through EPRI's utility advisory committees and through public forums. Finally, a very important aspect is the initiation and coordination of a business plan for commercialization of OCMHD technology. The goal of this effort will be to provide utilities with information so that well-founded decisions can be made on support of the OCMHD program, to encourage technical and financial involvement in the program by prospective equipment manufacturers, and to establish appropriate government cooperation in the commercialization of the technology.

With technical progress evident in all aspects of the program, OCMHD represents an important potential option for future power generation from coal and merits serious attention by the electric utility industry. EPRI, through its active and planned efforts in this area, can play a key role in the continued development and eventual commercialization of OCMHD technology. *Project Manager: Paul Zygielbaum*

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Correction

In Figure 1, page 27 in the March JOURNAL status report on Coal Cleaning, the phrase "Fine-coal cleaning" should be substituted for "Flue coal cleaning."

Coal-Oil Emulsions for Boiler Fuel

by H. H. Gilman

Can an oil-fired power plant stretch its fuel supply by mixing in some pulverized coal? EPRI joined with General Motors, ERDA, and others to test the scheme. Conclusions are technically encouraging, but economic justification is limited. ▫ An EPRI technical article

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Unavailability of fuel oil for a power plant that had been converted from coal to oil firing might tempt management to convert back to coal. In most such cases, if conversion is possible, it probably would be cost-effective to make the change and pay out the project with reduced fuel costs. At some plants, however, conversion is impractical. A plant originally may have been designed for coal, but the coal storage and handling facilities no longer exist. Or, conversion of an old plant cannot be justified before its scheduled retirement. Despite these cases, a scenario can be imagined that would require conversion to be considered because of fuel oil supply limitations.

Burning a coal-oil mixture is suggested as a near-term means to minimize plant conversion problems and expense, in at least some situations, while reducing the dependency on oil. The technique has recently been investigated in research sponsored by EPRI, with additional funding or participation by General Motors Corp., ERDA, and more than 15 companies—electric utilities, coal and oil producers, engineers, and suppliers. (EPRI RP527, Boiler Firing Test With Coal-Oil Emulsion. The final report is being prepared by General Motors and publication is expected mid-1977.)

Precedent in history

History certainly indicates that coal-oil mixtures can be burned as fuel. The first attempts were made over 100 years ago. In this century, Navy tests on the U.S.S. *Gem* in 1917 were satisfactory. A locomotive boiler was successfully fired in England in 1922. And in 1932 the Cunard liner *Scythia* steamed from Liverpool to New York and back with one boiler fired on a coal-oil slurry. There were other successful tests of coal-oil mixtures in Japan, Germany, and the USSR. Investigations at the Canadian Combustion Research Laboratory resulted in a symposium in 1972.

Despite this recurring interest, no significant economic advantages became apparent, and none of the experiments led to commercialization. Today, the relative costs of coal and oil, regulatory agency directives, and possible curtailment of oil for boiler fuel may change that picture for certain applications.

Research scope

Coal-oil fuel can be merely a mixture of coal and oil requiring continuous agitation to prevent settling, a colloidal suspension requiring extensive coal pulverization, or a stable emulsion of coal, oil, and water with an emulsifier additive. There are relative advantages to each. For example, an emulsion has the advantage of being stable without continuous agitation, but it requires a suitable low-cost additive.

The primary purpose of EPRI-sponsored research was to fire a small industrial boiler with an emulsion and obtain data to identify new technical requirements, as well as to determine the economic potential. The focus of the project was on slurry preparation, burner design, emission controls, ash removal, boiler operation, and economic analysis.

Additional testing at utility plants was deemed necessary and ERDA is considering further development and demonstration activity in cooperation with other companies. Among them, New England Power Service Co. is investigating combustion stability of coal-oil mixtures and will conduct firing tests at New England Power Co.'s 80-MW Salem Harbor No. 1 unit. Also, the City Public Service Board of San Antonio, Texas, expects to investigate the adaptability of a 69-MW natural-gas-fired boiler to coal-oil slurries. EPRI anticipates supporting further research based on needs apparent at completion of the GMC work and further discussions with utilities and boiler manufacturers.

Slurry preparation A stable emulsion is essential for good flame stability and also to keep the coal from settling out in tankage and lines. To suspend prewetted coal particles in the oil-in-water emulsion, a proprietary emulsification chemical was used.

Laboratory tests indicated that the emulsion was completely stable, with no settling. However, during the boiler test there was 5% settling, probably due to incomplete emulsification of the oil and water. This degree of instability did not cause operating problems but is unacceptable for storage. More mechanical mixing energy may have to be put into the emulsification process to produce a stable emulsion.

Except for the additive cost (40–50¢/10^6 Btu), no major difficulty is anticipated in making a commercially acceptable, stable coal-oil emulsion. New development or economies derived from large production could drop the additive cost. The range of 10–20¢/10^6 Btu is considered an acceptable goal.

Burner design Combustion tests were directed by Systems Research Laboratories at the Institute of Gas Technology (IGT) combustion laboratory. The tests involved using steam- and air-atomized burners in a test tunnel furnace to investigate flame geometry, stability, emissivity, and NO_x emissions. Slurry emissivities were either the same as or higher than the values obtained from No. 6 fuel oil. The presence of 5% water in the fuel did not degrade combustion.

Boiler-firing tests used an oil-fired, flat-bottomed, 120,000-lb/h Wickes boiler that generates saturated steam at 250 psig to meet a heating load at the Saginaw Works of General Motors. The boiler has natural draft with no flue gas clean-up equipment and no air preheat.

The burner could be switched from slurry to oil with minor air register adjustments. Lighting off the boiler on slurry was demonstrated. Both steam- and air-atomized burners were used, the latter giving the better performance (Table 1). Because of their smaller ports, the steam-atomized burners had a greater tendency to plug.

Emission controls Slurry fuel of an acceptable sulfur content was made by blending low-sulfur fuel oil and 2–3% sulfur coal (Table 2). Whether such fuel will be consid-

Table 1

BURNER CHARACTERISTICS: OIL VERSUS SLURRY

(air-atomized Forney-Verloop burner)

	No. 6 Fuel Oil	*Coal Slurry*
Steam flow rate (lb/h)	40–45,000	40–45,000
Fuel pressure (psig)	116	140
Oxygen (%)	5.2–8.0	4.1–7.6
NO (ppm)	155–198	265–328
CO (ppm)	6–33	4–25
Particulate emissions (avg gr/acf)	0.0153–0.0188[a]	0.373–0.472[b]
Opacity (%)	0–8	32–35

[a]0.03 lb/1000 lb gas.
[b]0.68 lb/1000 lb gas.

Table 2

FUEL ANALYSES: OIL VERSUS SLURRY

	No. 6 Fuel Oil	*Coal Slurry*
Heat content (Btu/lb)	19,049	15,975
(Btu/gal)	146,906	136,922
Sulfur (%)	0.57	0.88
Ash (%)	0.056	3.92
API gravity @ 60°F	21.3	6.0
Weight @ 60°F (lb/gal)	7.712	8.571
Viscosity @ 100°F (cs)	509	—
Carbon (%)	87.3	78.45
Hydrogen (%)	11.3	16.8
Nitrogen (%)	0.51	0.66
Oxygen (%)	0.28	0.17
Vanadium (ppm)	21	14

ered by regulatory agencies as an "oil" or a "coal" was resolved by EPA's ruling that the emission limitation be the average of the individual fuel standards, weighted according to their proportions in the mixture.

The test boiler has no particulate collection equipment. During the test the stacks produced gray smoke with 30% average opacity, which was unacceptable. Evaluation of emissions led to a conclusion that a precipitator or bag filter is necessary.

Ash removal When coal-oil slurry is burned under a boiler originally built for coal firing, the boiler's hopper bottom aids in ash removal. A flat-bottomed boiler, normal in oil-fired designs, requires special attention. The R&D solution was a soot blower designed to travel continuously back and forth across the boiler floor and sweep ash into a trough at the far end for removal in a water slurry. It worked very well. Most of the light ash was reentrained in the flue gas stream rather than swept to the far end. However, the heavier ash particles were removed in the water trough. It was found unnecessary to run the machine continuously.

Different coals will produce different ash deposits. However, either a traveling design as tested or stationary steam nozzles to reentrain the ash seems to be a practical solution for ash handling.

Table 3

COST COMPARISON: COAL–OIL EMULSIONS

Ingredient	*Concentration (lb/lb)*	*Higher Heating Value (Btu/lb)*	*Cost ($/10⁶ Btu)*	*Ash (%)*	*Sulfur (%)*
40% Coal					
No. 6 fuel oil (15 API)	0.570	18,675	2.50	0.2	0.5
Coal (Kentucky bituminous)	0.400[a]	13,350	1.00	9.0	2.5
Water	0.023	0	0	0	0
Emulsifier ($1/lb)	0.007	0	0.44	0	0
Emulsified fuel mix	1.000	15,984	2.44[b]	3.7	1.2
50% Coal					
No. 6 fuel oil (15 API)	0.470	18,675	2.50	0.2	0.5
Coal (Kentucky bituminous)	0.500[c]	13,350	1.00	9.0	2.5
Water	0.023	0	0	0	0
Emulsifier (50¢/lb)	0.007	0	0.22	0	0
Emulsified fuel mix	1.000	15,452	2.09[b]	4.5	1.5

[a]33% on Btu basis.
[b]Not including slurry preparation costs.
[c]43% on Btu basis.

Boiler operation Data at high loads were not obtained with the General Motors boiler, so it is difficult to evaluate any reduction of nameplate rating when burning slurry. Tests are to be made at high loads, and the findings and their significance will appear in the research project report. At medium loads (60,000–75,000 lb/h) the boiler required 30–40% excess air to keep the stacks reasonably clean.

The boiler responded to load changes with no problem. No slagging was observed on the walls after about 200 hours of slurry operation. The wall tubes were clean. There was a light buildup of ash on horizontal surfaces in the convection section, but it was easily removed by a soot blower. Although some deposit was observed to grow at the tip of the burner, it was soft and easily blown off with a steam lance.

Economic analysis During tests there was difficulty in maintaining a constant 40% slurry concentration. However, this could be overcome with more operating experience. (A 50% coal concentration should be attainable in the future, making the economics more attractive but also increasing the sulfur and ash concentration of the slurry.)

The cost of a 40% coal-oil slurry (Table 3) is little better than the cost of oil alone: $2.44 versus $2.50/10⁶ Btu. Therefore, with the added cost of a preparation plant, particulate emission controls, and ash-handling equipment, there would be no overall economic incentive to burn coal-oil emulsions. Motivation would exist only if oil was cut back and conversion of a specific plant to coal firing was either not possible or not economically attractive.

With further development it is reasonable to expect higher concentrations of coal and lower costs for the additive, such as in the 50% coal-oil slurry of Table 3. The sensitivity of slurry cost to coal concentration and additive price is apparent, and the basic conclusion is unchanged: Coal-oil slurry firing is an attractive alternative only when conversion of an oil-fired boiler to coal is not practical.

Technical justification

It appears that oil consumption can be reduced by approximately 40% on a Btu basis by using coal-oil slurries and that conversion of a plant to accept slurry fuel can be accomplished with a minimum of downtime. Although some further development of technology is desirable, coal-oil fuel is a near-term alternative for small utility and industrial boiler applications. As analyzed to date, operating costs are higher than for straight coal, but they compete with oil on a Btu basis.

An extremely attractive feature of the coal-oil slurry concept is that an extensive new technology doesn't need to be developed before application. The fuel could be commercially available within two years, with a minimum requirement for new equipment and technology.

Since preparation of the coal-oil mixture is complicated and expensive, a central slurry preparation plant can be visualized that prepares and ships a stabilized fuel mixture to outlying power plants. Fuel blending may become a new business venture. Small users could buy blended fuel and presumably interchange slurry fuels and oil with a minimum of turn-around effort and expense. Larger users could justify their own preparation facilities.

For boilers originally designed for oil, conversion to coal is unlikely to be practical without serious derating of the plants. Management would undoubtedly allocate available oil to these plants as long as possible to avoid the tremendous expense of downtime and conversion. But, to conserve oil for such plants where oil is essential, it makes sense to adapt small stations and industrial boilers to coal-oil mixtures.

New Technical Reports

ELECTRICAL SYSTEMS

Superconducting Fault Current Limiter
EL-329 Final Report (RP328)

This report evaluates the use of a superconducting element as the active part of a fault current limiter for power utilities. Such a device is technically feasible over a wide range of parameters for the required electric power source and material properties of the superconductors available. Limiting is achieved by driving the superconductor into its resistive state and commuting the current into a shunt resistor. For a three-phase, 145-kV (rms), 2-kA (rms) line, the total cost, excluding installation in the power system and shunt resistor, is approximately $300,000. The specific advantages and disadvantages are indicated, as well as the outstanding problems to be tackled next. *Argonne National Laboratory*

Fundamental Investigation of Arc Interruption in Gas Flows
EL-284 Final Report (RP246-1)

This document reports work of a multidisciplinary team on physical and aerodynamic processes involved in early, or thermal, recovery of gas blast interrupters. Nozzle and electrode geometry investigations exhibited a sharply defined optimal position for the upstream electrode with respect to the nozzle throat. A diffuse arc section, contributing very little to the recovery speed, was found at the downstream end of nozzles in which large divergence angles and/or low nozzle pressure ratios led to separation of the flow from the wall and associated internal shock waves.

Investigations of model testing techniques revealed that recovery speed (RRRV) is independent of power frequency over a wide range, provided nozzle blocking and metallic electrode vapor contamination are avoided. *General Electric Co.*

ENERGY ANALYSIS AND ENVIRONMENT

Residential Demand for Energy
EA-235 Final Report, 2 Vol. (RP431)

This publication reports on residential energy demand from 1956 to 1972, with principal emphasis on demand for electricity. In order to deal with decreasing block pricing in the sale of electricity in a manner that is theoretically appropriate and econometrically sound, a new price data set was constructed from actual residential rate schedules published in the National Electric Rate Book. The price of electricity is represented in the econometric demand functions as the marginal price plus a measure of intramarginal expenditure. The basic unit of observation is the state, and the models are estimated using the variance-components technique.

Two types of dynamic models are estimated: (1) logarithmic flow-adjustment models in which appliance stocks do not appear explicitly and (2) stock-adjustment models in which they do. The latter employ annual estimates for the years 1960 to 1972 of 11 types of electrical appliances. *Data Resources, Inc.*

Determination of the Feasibility of Ozone Formation in Power Plant Plumes
EA-307 5 Vol. (RP572-1, 2)

This publication reports on investigations conducted in cooperation with the University of Washington Cloud Physics Group regarding the potential for ozone formation in the plumes of coal- and gas-fired power plants in the southwestern U.S. It includes a review of pertinent scientific literature, a collection of extensive air quality and meteorological data by two aircraft at three southwestern power plants, analysis of the data, and testing of a computer simulation model for chemically reactive plumes.

The results of this research are described in five volumes:

Volume I: Executive Summary
Volume II: Final Report
Volumes III–V: Data Summaries

A topical review of techniques for characterizing power plant plumes (EC-144) and a final report on the University of Washington's investigations (EA-270) have been published separately. *Meteorology Research, Inc., and Systems Applications, Inc.*

Effects of Electric Fields on Large Animals
EA-331 Interim Report (RP799-1)

This interim report briefly describes progress toward the establishment of a colony of Hanford miniature swine (HMS) for long-term study of the effects of 60-Hz electric fields on development and physiologic function. Major tasks to date have included: design and erection of an electrode system to provide uniform, vertical fields of large magnitude; design of nonconducting housing meeting criteria of durability and electrical acceptability; and establishment of a breeding protocol for the first generation of HMS.

This animal was developed by selective breeding for laboratory use as a stand-in for man. Effects in linemen and switchyard workers noted by the USSR (nausea, loss of appetite, etc.) reportedly occurred after prolonged and repeated exposure to HV fields. Similar effects have not been seen in the U.S. If such effects can be caused by strong electric fields, related responses should be demonstrable in the experimental animals.

This project is part of an EPRI-sponsored biological research program comprising a balanced spectrum of HV investigations. The overall program includes projects concerned with effects on specific ecosystems, on cardiac pacemakers, and on behavior of social insects, and with the development of a data base designed to maintain awareness of worldwide research in this area. *Battelle, Pacific Northwest Laboratories*

FOSSIL FUEL AND ADVANCED SYSTEMS

An Assessment of Energy Storage Systems Suitable for Use by Electric Utilities
EM-264 Final Report, Vol. III (RP225)
(ERDA E(11-1)-2501)

This volume provides expanded treatment of the material on conventional and underground pumped hydro plants in Vol. II. It describes their current state of development and characterizes their typical, or expected, unit sizes, head, efficiency, charge/discharge ratio, reliability and availability, storage capacity, turnaround time, life, and siting potential.

Principal findings are that hydro pumped storage is a well-developed, mature technology. Where suitable sites are available for two surface reservoirs, no technical obstacles exist to impede implementation. Underground reservoirs may extend the areas where hydro pumped storage can be used, and further development of high head equipment will be desirable for use in high head underground plants. *Public Service Electric and Gas Co.*

Development of Sodium-Sulfur Batteries for Utility Application
EM-266 Annual Report (RP128-3)

The results of this past year's work (part of a multi-year program) have considerably strengthened our previous opinion that the sodium-sulfur battery will meet all technological requirements of a successful load-leveling and peaking system. The emphasis of the total program has been to demonstrate that high capacity, long life, and high efficiency can be obtained from the sodium-sulfur system, using economical materials and practical fabrication methods. This year, the testing and study of small cells was accelerated, and new programs on module and system design were initiated.

This report includes discussion of two initial cell/module/system designs (the cells consisting of many individual beta-alumina tubes separating single sodium and sulfur compartments). It also includes the results of heat conduction experiments, a thermal analysis of the system, and a comparative cost analysis. Supporting research is also presented, including corrosion studies on container materials, sodium motion and defect structure in beta-alumina, pressure-temperature stability of beta and beta-alumina, and the effects of grain orientation on the electrical properties of beta-alumina. *General Electric Co.*

Evaluation of Regenerable Flue Gas Desulfurization Processes
FP-272 Final Report, 2 Vol. (RP535-1)

This report evaluates eleven regenerable flue gas desulfurization (FGD) processes on a common design and cost basis to assess their future potential and make recommendations regarding the level of additional developmental activities. (One throwaway FGD process, lime/limestone wet scrubbing, provides a "baseline" for process comparisons.) Due to the preliminary development status of many of these processes, capital investment costs are not estimated. Additional topics considered include reducing gas production, lime/limestone sludge regeneration, and sulfur versus sulfuric acid production.

Although capital costs have not been estimated, they will undoubtedly represent a major factor in the total annualized cost of these processes and will become the key to selecting one process over another. Designs and operating data currently available for most second-generation FGD processes do not appear adequate for scale-up to commercial-sized (100-MW) units. The choice of sulfur or sulfuric acid production is a criterion that will have a major impact on the cost of an FGD system and will have to be evaluated on a site-specific basis. *Radian Corp.*

Experimental Fusion Power Reactor Conceptual Design Study
ER-289 Final Report, 3 Vol. (RP323-1)

This final report describes a conceptual design study of a fusion experimental power reactor (EPR) and an overall EPR facility. The primary objective of the two-year program was to develop a conceptual design of an EPR that operates at ignition and produces continuous net power. A conceptual design was developed for a doublet configuration based on indications that a noncircular tokamak offers the best potential of achieving a sufficiently high β (the ratio of the plasma pressure to the pressure of the confining magnetic field—on the order of 0.10) to provide a viable reactor concept at reasonable cost. Other objectives included the development of a planning cost estimate and plant schedule and the identification of critical R&D programs required to support physics development and engineering and construction. *General Atomic Co.*

Electric Utility Solar Energy Activities
ER-321-SR Special Report

This report is an updated version of the *Preliminary Survey of Electric Utility Solar Projects, February 1976*. Like the initial survey, it has a threefold purpose: (1) to provide a basis for the exchange of information between individual utilities interested in the various project areas; (2) to assist EPRI solar energy project managers in developing programs responsive to utility needs; and (3) to inform representatives of state and federal agencies and commissions, and other appropriate individuals, of the range of interests and extent of participation of the electric utility industry in solar project demonstrations. Included for cross-reference are a list of utilities involved with projects designated by category and an address list of the utilities.

Guidelines for the Design of Mist Eliminators for Lime/Limestone Scrubbing Systems
FP-327 Final Report (RP209)

A remaining source of much difficulty in flue gas desulfurization (FGD) systems employing lime/limestone scrubbing is mist-eliminator (ME) plugging due to scaling and solids deposition. In this study, the various ME types, construction methods, configurations, and washing procedures employed in commercial systems on large-scale lime/limestone scrubbing installations were investigated on a plant-by-plant basis. The report presents basic information necessary for supervisory and operational personnel to select or modify an ME system.

Chevron and baffle-type mist eliminators are treated extensively. Radial vane, radial baffle, and electrostatic precipitator mist eliminators are covered to a lesser degree. Background information covers collection, reentrainment, mist eliminator failure mechanisms, and other factors affecting performance, cost, and collection efficiency. *Battelle, Columbus Laboratories*

Advanced Technology Fuel Cell Program
EM-335 Final Report (RP114-1)

In 1971 and 1972 studies showed that high efficiency in low ratings, modular design, and low pollution characteristics permit siting fuel cell generators at dispersed locations in the electric utility transmission and distribution network, with substantial benefit to the electric utility industry. Two efforts evolved from the initial activity: (1) to develop and demonstrate FCG-1, the initial dispersed generator, and (2) to establish the technical feasibility of advanced concepts to improve the economic characteristics, fuel flexibility, and operating flexibility of dispersed generators, and to estimate the potential characteristics of central station fuel cell power plants operating on coal. This report describes the results of these activities between April 1973 and March 1976.

Economics studies focused on the fuel cell power section and demonstrated that molten-carbonate fuel cell power plants are capable of meeting the program heat rate goal of 7500 Btu/kWh at a cost less than or equal to initial dispersed generators. Progress in extending molten-carbonate cell endurance was achieved and the initial scale-up to engineering hardware was demonstrated. New configurations promising lower cost phosphoric-acid fuel cell stacks were identified.

Fuel investigations included liquid fuel capability for dispersed generators and coal central station concepts. Hydrodesulfurization of naphtha was adapted to fuel cell conditions; catalyst endurance and the ability to use naphthas from a range of U.S. refineries were demonstrated. One study showed that a naphtha hydrodesulfurizer could be incorporated into the initial dispersed generator with minimum impact on power plant characteristics; this technology has now been incorporated into the FCG-1 power plant. *United Technologies Corp.*

Economic Assessment of the Utilization of Fuel Cells in Electric Utility Systems
EM-336 Final Report (RP729-1)

This study evaluates the long-range economic benefits of first-generation and advanced fuel cells in the future generation capacity plans of a representative electric utility system. The benefits of fuel cells' unique characteristics (such as lower heat rate, relatively flat heat rate characteristic, better availability, reduced construction lead time, and dispersed siting) are quantified separately in terms of reliability, production cost, and optimum generation mix methods commonly used in generation planning in utilities.

First-generation fuel cells appear to be attractive for intermediate duty in a utility expansion program if the EPRI projected goals of $250/kW installed capital cost and 9300 Btu/kWh heat rate can be met. The penetration of this generation will depend on factors specific to an individual utility such as fuel availability and cost, environmental constraints, load factor, and the other generation options coupled with the relevancy of special fuel cell penalties and savings. The second-generation fuel cells will have significant market penetration at installed capital costs of $200–$300/kW and a 7500-Btu/kWh heat rate.

This report discusses the relationships between market penetration, fuel price, and capital cost for the two fuel cell types and quantifies the various penalties and savings of fuel cell installation. *Public Service Electric and Gas Co.*

Coal-fired Power Plant Capital Cost Estimates
AF-342 Final Report (RPS0A76-329)

This study is part of a broad examination of the total cost of producing electricity from coal-fired and nuclear power plants in 1976 and over the next twenty years. EPRI will use this study as a reference document and also to improve industry and public understanding of such present and future electric power costs by widespread publication.

Capital cost estimates have been prepared for 100-MW coal-fired power plants in four regions of the United States: northeast, southeast, Great Lakes, and western. The plants were designed to burn regionally representative coals. For the Great Lakes location, cost estimates were made for both Illinois and Wyoming coals. For the western location, two Wyoming coal-fired plants were studied, one designed to EPA new source performance standards and the other designed to New Mexico emission standards. The effect of building the plant on a remote site was also studied for the western location. *Bechtel Power Corp.*

NUCLEAR POWER

A RELAP4 Analysis of the GE BWR Blowdown Heat Transfer Two-Loop Test Apparatus Experiments, Tests 4902, 4903, 4904 and 4906
NP-169 Final Report (RP444-1-1)

This report presents the results of modeling studies of the RELAP4 thermal-hydraulics code to predict the blowdown response of the General Electric Two-Loop Test Apparatus (TLTA). The TLTA is a scale-model test system used to simulate BWR blowdown transients. Areas investigated in the study included the selection of critical flow multipliers to be applied at the break area, the geometric input modeling of the broken loop jet pump, and the use of alternative assumptions in defining the phase separation in the lower plenum. The results of these studies were compared with experimental data from various break size tests performed in the TLTA experiments.

This project is one of a series sponsored by EPRI that involves the verification and development of thermal-hydraulic computational methods and participation in the Nuclear Regulatory Commission's (NRC) "Comparative Analysis of Standard Problem" (CASP) program. *Energy Incorporated*

Mechanical Fracture Predictions for Sensitized Stainless Steel Piping With Circumferential Cracks
NP-192 Final Report (RP585-1)

Circumferential intergranular stress corrosion cracks have been discovered in the heat-affected zones of girth welds in the Type 304 stainless steel recirculation bypass systems of several BWRs. These cracks initiate at the inner surface of the pipe wall and grow through the thickness by combined stress corrosion and fatigue. The work outlined in this report is based on the supposition that such a crack has been detected and that its size and shape are known. To determine the residual strength of the cracked pipe, an integrated program of small-scale laboratory experiments, full-scale pipe tests, finite-element computations, and a mechanical failure analysis was conducted. A simple plastic collapse criterion can be used effectively to predict failure. On this basis, the report provides a predictive method for determining (1) the failure point of a cracked pipe under combined bending and internal pressure loading and (2) the applied load-crack size combinations under which a leak-before-break condition might be expected. Recommendations for further study are also given. *Battelle, Columbus Laboratories*

Comparison of RELAP4 Predictions With Standard Problems 1, 2, and 3

NP-205 Key Phase Report (RP444-1-2)

This report contains the results of RELAP4 best estimate calculations of standard problems 1, 2, and 3, including comparisons with experimental data. These analyses were performed to assess the capability and identify areas of the RELAP4 code that need further improvement. RELAP4 is a digital computer program developed to predict the thermal-hydraulic behavior of experimental systems, such as water-cooled nuclear reactors subjected to postulated transients.

Standard Problem 1 was based on the straight pipe depressurization experiments performed by Edwards et al in Great Britain. Standard problems 2 and 3 were based on an isothermal blowdown of the 1½-loop semiscale system, Tests 1011 and 1009, respectively, and were similar experiments except that an emergency core coolant (ECC) injection system was added to the latter problem.

In addition to comparisons with experimental data, several sensitivity studies were performed on Standard Problem 1. In these studies, several deficiencies were discovered, including coding errors in the critical flow multiplier and form loss coefficient when used with a time variant valve, and the average volumetric flow calculation when related to the treatment of momentum flux. Additional areas of deficiencies identified from the studies of standard problems 2 and 3 included the separation model used in the lower plenum and the prediction of wall surface temperatures. The RELAP4 calculated overall response of the three standard problems in comparison to the experimental data was quite satisfactory with the exception of the ECC injection effects. *Energy Incorporated*

A Study of Crack Growth Under Operational Conditions in Steam Turbine Steel: Phase 1

NP-325 Technical Report 9 (RP700-1)

This two-phase study is part of an EPRI program to develop a steam turbine rotor bore life prediction system. The data required for the calibration of this analytic system derive in part from boresonic inspections of retired rotors. The subsequent cutting and sectioning of these rotors permit metallurgical analyses that yield detailed information on flaw sizes, orientations, and distributions, and also specimen fabrication and tests that generate materials behavior data. Further calibration data are available in the open literature, but certain information must be provided by separate research efforts. The work effort described in this report is directed to this latter need.

This report evaluates those factors which control the initiation, stable growth, and rupture of bainitic Cr-Mo-V rotor steels under operating conditions. Phase 1 has concentrated on the effects of cyclic loading and repeated strain aging, during steady-state operation, on fatigue crack growth and rupture. Material has been tested from air melted rotors removed from service after about 20 years and newer rotor forgings, which are vacuum degassed to reduce the number of inclusions. *Failure Analysis Associates*

Fracture of Zircaloy Cladding by Interactions With Uranium Dioxide Pellets in LWR Fuel Rods

NP-330 Technical Report 10 (RP700-1)

Power reactor fuel rod failures can be caused by uranium dioxide fuel pellet–Zircaloy-cladding interactions. This report summarizes a detailed theoretical study of Zircaloy-cladding fracture caused by the growth of stress corrosion cracks that form near fuel pellet cracks as a consequence of a power increase after a sufficiently high burnup. Stress corrosion crack growth in irradiated Zircaloy must be able to proceed at very low stress intensifications if uniform friction effects are operative at the fuel-cladding interface, when the interfacial friction coefficient is less than unity, when a symmetric distribution of fuel cracks exists, and when symmetric interfacial slippage occurs (i.e., "uniform" conditions). Otherwise, the observed fuel rod failures must be due to departures from "uniform" conditions, and a very high interfacial friction coefficient, and particularly fuel-cladding bonding, is a means of providing sufficient stress intensification at a cladding crack tip to explain the occurrence of cladding fractures. *Failure Analysis Associates*

Utilization of Ultrasonic Tomography for the Mapping of Residual Stress Fields in Thick Metal Sections

NP-338 Final Report (RP504-1)

In the past it has not been possible to measure or accurately calculate residual stresses in thick metal structures. As a result, designers, structural analysts, and regulators have had to make conservative assumptions of structural residual stress. In an evaluation of the safety of a flaw in a heavy steel structure, all stresses, including residuals, must be accounted for. If conservative values of residual stress are used in flaw evaluation calculations, structures that are, in fact, safe (were actual residual stresses known) might be shut down for unnecessary repair. The objective of this project was to determine the engineering feasibility of nondestructively measuring residual stress in thick steel sections and thereby eliminating the necessity of making a conservative stress assumption.

The velocity of sound propagation through a solid is altered when a stress is applied. The velocity change is small and dependent on the type of wave being propagated as well as the magnitude of the stress. This report describes the successful preliminary work done in measuring this velocity change, evaluating computerized reconstructions of velocity fields from velocity profiles, and constructing residual stress maps from velocity field information. *Battelle, Pacific Northwest Laboratories*

Numerical Simulation of Hydrodynamic Response of Mark I Suppression Pools

NP-345 Key Phase Report (RP693-2)

EPRI is currently sponsoring several studies to quantify the loads in a Mark I containment system during a postulated loss-of-coolant accident. This program will develop and verify numeric models to simulate pool swell. The program has produced two numeric models (codes) that together calculate the kinematics and the dynamics of the pool swell from the initial drywell pressurization to shortly after ringheader impact. The VENT/3 code covers the period from the initial drywell pressurization to the time when water in the downcomer is completely expelled. The SURGE code traces the evolution of the bubbles and hydrodynamics in the wetwell after vent clearing. This report describes the SURGE code (MOD 1), which treats the air as an incompressible. A future report will describe SURGE (MOD 2), incorporating compressibility. *Jaycor*

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