Rivalry in Residential Heating

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

Cover: Competition between electric and gas technologies is creating a wider choice of energy-efficient devices for home space conditioning.

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Competition and Technological Innovation

For more than a century, electric and gas companies have been competing to provide better service to their customers. The first major area of competition was lighting, which ended in complete domination of this sector by electricity. After declining rapidly following the introduction of the electric light bulb, the last remaining gas lighting systems were retired during the early 1970s to help provide an adequate supply of natural gas for more economically competitive uses. Similarly, for many years natural gas effectively provided energy for refrigeration in the residential sector. Although a few of these units still remain in service, this market has also yielded to domination by electricity.

Such historic shifts resulted from competition driven primarily by two factors: changing relative costs between the two rival energy forms and constantly improving technologies for both gas and electricity. Technological innovation and improvements in energy efficiency have helped moderate the last decade's rapid escalation of energy prices. As R&D continues, even more improvements in efficiency can be expected, together with greater product flexibility and convenience.

The principal beneficiaries of these improvements have been individual consumers, particularly in the residential sector, where all our lives have been made more comfortable. Today gas and electricity still compete in four important areas of the residential market. By far the largest of these is home heating, followed by water heating, cooking, and clothes drying. The contribution made in these areas by other forms of energy is very small, and virtually all the appliances used in other residential applications run exclusively on electricity.

In terms of total energy consumed, residential heating and cooling is extremely important, and the competition between electricity and gas remains especially keen in this market segment. This month's cover story describes some of the factors that will help determine the future of the competition, with particular emphasis on the development of new technologies that provide convenience and comfort at lower cost.

Traditionally, technological innovations in household appliances have come primarily from their manufacturers. Today, however, corporate takeovers, reorganizations, and changes in product strategies appear to have reduced this industry's R&D efforts. Because many of the benefits of technology improvement accrue to the customers of utilities—both electric and gas—the next generation of advanced heating and cooling technologies will be influenced by the participation of EPRI and the Gas Research Institute (GRI) in R&D programs.

Although GRI's overall R&D budget is only about two-thirds of EPRI's, its funding for research on residential heating and cooling technology is currently several times larger. This emphasis reflects a recognition by the gas industry that the traditional gas-fired furnace can now be challenged by new, highly efficient electric heat pumps throughout many parts of the country.

However, EPRI's research focus, which has traditionally centered on supply-side issues, is increasingly emphasizing energy utilization, particularly R&D on end-use technologies. EPRI's growing effort in the residential heating and cooling area focuses on improving the performance of electric heat pumps so they can penetrate markets in increasingly colder climates. GRI's research, in turn, includes several major projects aimed both at increasing the efficiency of gas furnaces and at developing a commercially viable gas-fired heat pump for the commercial and residential markets.

Improvements in equipment and in the thermal integrity of buildings have already made the delivery of heat to homes at least twice as efficient as in the 1950s. Even more gains are likely to result from further research, because current heat pumps are only about 20% as efficient as is theoretically possible. In addition, improvements can also be expected in product price, convenience, delivered comfort, reliability, and servicing. Although it is still too early to predict the outcome of the competition between gas and electricity in residential heating and cooling, both resources will probably find secure market niches for some time to come.

More is at stake in this competition, however, than just the sale of new appliances and the electricity or gas to run them. Many utilities provide their customers with both forms of energy and are members of both EPRI and GRI. Their continued support for both sides in the current technology race reflects a confidence that further improvements in end-use equipment can benefit all concerned. For utilities, the availability of improved heating and cooling appliances can provide new opportunities for energy conservation, valley-filling, and strategic load growth. For consumers, the current wave of competition will mean a wider range of heating and cooling options, so they can choose equipment and balance initial investment against operating costs to suit individual needs. In the long run, both utilities and their customers will benefit from any developments in technology that are able to promote the most productive use of gas and electricity.

Thomas R. Schneider, Director
Energy Utilization and Conservation Technology
Energy Management and Utilization Division

Authors and Articles

Competition in heat pumps is the main event of today's rivalry between electric and gas energy for space heating in houses. **Competition Heats Up in the Residential Sector** (page 6), this month's lead article, states that the rival developments are also a useful hedge against uncertain future prices of both energy forms. The article is the work of science writer John Douglas, guided by two research managers of EPRI's Energy Utilization and Conservation Technology Department.

Arvo Lannus manages the research program dealing with residential and commercial applications. An Institute staff member since May 1980, he was formerly with Gordian Associates, Inc., for six years, much of that time as director of advanced technology and responsible for consulting activities in energy-efficient equipment and practices. Earlier, Lannus was on the chemical engineering faculty of Cooper Union School of Engineering for four years. He has a BS in chemistry and a PhD in chemical engineering, both from Drexel University.

James Calm works with Lannus as project manager for heat pump development. He came to EPRI in July 1981 from Argonne National Laboratory, where he had worked for five years in R&D on heat pumps and other technology for energy conservation. While in the Air Force from 1971 to 1976, he held operating and engineering responsibilities for various heating, air conditioning, and refrigeration systems. Calm has a BS in mechanical engineering and an MS in engineering design, both from Tufts University.

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Changes in forests over the last 10 or 20 years have polarized industrial and environmental factions in the United States and abroad. **Forest Stress and Acid Rain** (page 16) reviews some of the detective work being done by forest ecologists to identify sources and mechanisms of stress. Feature writer Michael Shepard developed the article with the aid of three research managers in EPRI's Energy Analysis and Environment Division.

John Huckabee, a staff member of the Environmental Assessment Department since May 1979, became manager of the Ecological Studies Program in February of this year. His earlier project responsibilities suggest the scope of the program: toxic substances, atmospheric deposition, and their effects on terrestrial and aquatic systems. Huckabee was formerly on the research staff of the environmental sciences division at Oak Ridge National Laboratory for eight years. In addition to a BS in biology from Sul Ross State University (Texas), he has an MS in zoology and a PhD in physiology, both from the University of Wyoming.

Robert Goldstein is a senior project manager with Huckabee. He has been with EPRI since April 1975, successively focusing on aquatic systems and on atmospheric deposition. Goldstein also was formerly with the environmental sciences division at Oak Ridge, working there as a systems ecologist for five and a half years. An engineering graduate of Columbia University, he holds MS and PhD degrees in nuclear science and engineering from the same school.

Louis Pitelka came to the Ecological Studies Program in December 1984, taking responsibility for research projects involving plant biology. Previously, he was with the National Science Foundation as director of a program in population biology and physiological ecology, and for nine years he was on the biology faculty at Bates College (Maine), where he became department chairman. Pitelka has a BS in zoology from the University of California at Davis and a PhD in biological sciences from Stanford University.

■

Evaluating the benefit of home energy conservation measures without waiting for a year of truly average weather is the promise of a recently developed computer program now in experimental use by three electric utilities. **Scoring High on Conservation** (page 26), by science writer Mary Wayne, reports on a model that normalizes home energy use on the basis of records for any year. Wayne's data source was Gary Purcell of EPRI's Energy Utilization and Conservation Technology Department.

Purcell is a project manager in the Residential and Commercial Program. He has worked primarily with measurement and control instrumentation for space conditioning systems since he came to EPRI in August 1977. Purcell previously was with Lockheed Missiles & Space Co., Inc., for 15 years as a thermodynamics engineer for the design, test, and analysis of aerospace vehicle temperature control systems. A mechanical engineering graduate of Oklahoma State University, Purcell also has an MBA from Pepperdine University (California).

■

First designing methods for efficient industrial management, later establishing practices for efficient government, Raphael Thelwell today is a professor at Howard University, a researcher in economic policy, and a member of EPRI's Advisory Council. From his years in federal budget analysis, augmented by an interim project with NAACP, Thelwell is watchful for economic incentives that produce widespread benefits but generate very localized costs. This month's profile, **Raphael Thelwell: Pursuing the Social Economics of R&D** (page 31), draws on ideas voiced in an interview with feature editor Ralph Whitaker.


Lannus


Calm


Goldstein

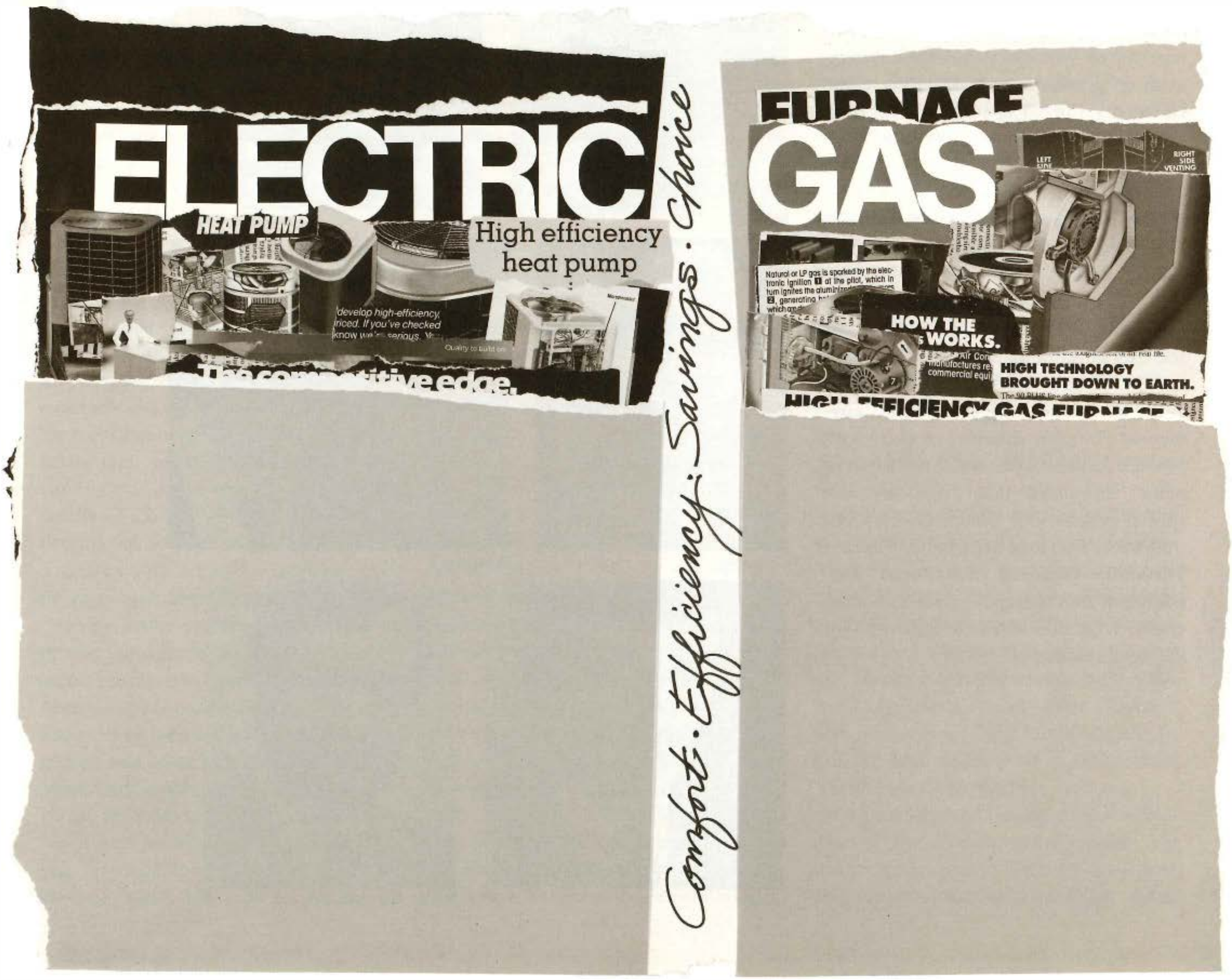

Huckabee


Purcell


Pitelka

COMPETITION HEATS UP IN THE RESDENTIAL SECTOR

Operating efficiencies are being boosted higher and higher as electricity and gas fight for the same territory in the residential heating and cooling market. The development of advanced heat pumps—both electric and gas—is the next step in expanding the array of space-conditioning technologies for the consumer.



The competition between gas and electricity for the lead role in residential heating is rapidly growing more intense. New technologies are challenging traditional patterns of energy use, uncertainties cloud the future of fuel prices, and almost any gain made by either electricity or gas in this crucial market comes at the expense of the other, since other energy sources play much smaller roles.

The stakes are high for both the gas and electric utility industries. In the past, gas-fueled devices dominated residential heating, accounting for nearly two-thirds of existing central heating systems. But as gas prices have risen and as electric heating appliances have become more efficient, electricity has made substantial penetration into the residential space-heating market. Over the last decade, approximately half of new single-family houses and two-thirds of new multifamily dwellings were built with electric heating.

One of the reasons for this market penetration is the increased acceptance of zoned heating—the use of small resistance heaters to warm one room at a time at much less cost than operating a central, forced-air furnace. These heaters have been chosen for use particularly in the smaller, more tightly insulated houses that have become increasingly popular in recent years. Another factor influencing the trend toward electric heating is the development of improved electric heat pumps, which were installed in about 30% of new single- and multiple-family dwellings in 1984. There are several reasons for their growing popularity. Not only are heat pumps a much more efficient way to heat buildings, but they also provide air conditioning in the same package—an important consideration in the sunbelt states, which have experienced the most rapid growth of new housing. Heat pumps may also benefit electric utilities by offering seasonal load management for summer-peaking utilities and selective load growth for winter-peaking utilities.

To help maintain the heat pump's competitive edge, the electric utility industry has directed EPRI to devote increasing amounts of research toward making these unique devices even more efficient and reliable for home use. At the same time, the gas utility industry has become more aggressive in trying to protect its vital interest in the residential heating market. In 1982 the American Gas Association (AGA) launched what it called "an aggressive, hard-hitting, anti–electric heat pump information campaign." The industry also has given increasing support to an extensive research program through the Gas Research Institute (GRI) to develop more efficient gas furnaces and heat pumps. Gas-fired heat pumps are not now commercially available for residential use in the United States. Their successful development would enable gas utilities not only to provide a more efficient heating option but also to challenge electricity's almost total dominance of air conditioning.

It is still too early to predict the outcome of this competition in any detail, but the real winner will almost certainly be the consumer. As a result of current research efforts, both gas and electricity customers will be able to choose from a wider variety of options for space heating and cooling and to save money by using more efficient devices for both energy sources. At the same time, it seems likely that many of the new electric and gas-fired units will be able to find successful niches in the diverse American space-conditioning market. Which of the two energy sources will dominate in any particular time or place will probably depend on a variety of local factors, including relative fuel prices and expected escalation rates, gas availability, equipment costs, and consumer awareness.

Forces behind the competition

The competition between electricity and gas began in the latter part of the nineteenth century, when Thomas Edison's incandescent lamp and central-station electric generators brought the gaslight era to a dramatic close. The gas used for lighting had, for the most part, been manufactured from coal and distributed by municipal utilities, which quickly had to shift emphasis toward marketing their product for cooking and water heating. Natural gas, as such, did not become a major competitor until abundant resources were discovered by a rapidly growing petroleum industry and until considerable improvements were made in pipeline technology. Sales of natural gas did not exceed those of manufactured gas until 1935, and the amount of energy derived from gas surpassed that of coal only in the late 1950s.

Because natural gas resources have been found in locations far removed from the ultimate consumers, an exceptionally complex industry has developed. Of the top 20 U.S. gas producers, 16 are integrated oil companies, but a total of about 3750 firms sell gas on the interstate market. The transmission of natural gas takes place via pipelines that exceed U.S. railroads in total mileage and that are primarily owned by 99 major interstate pipeline companies. Some 1350 separate utilities, which include both municipal agencies and private companies, are involved in distributing gas to consumers. Many of these utilities—including approximately one-quarter of EPRI members and one-half of GRI members—sell both gas and electricity.

Since the late 1930s, the price of gas sold in interstate markets has been controlled by the federal government, first by the Federal Power Commission and more recently by the Federal Energy Regulatory Commission (FERC). In 1978 the Natural Gas Policy Act brought producer sales of intrastate gas under FERC regulation as well. In a number of instances, the regulated price of gas made it more attractive in comparison with electric power. Recent moves to deregulate the gas industry add yet another complicating factor to the continuing competition between these two sources of energy.

Even before the spectacular rise of energy prices in the 1970s, the ratio of electricity price to gas price had been falling sharply, and this decline has continued. In 1970 the national average price ratio per thermal equivalent unit was about 6 to 1; by 1984 it was about 3.8 to 1. But these price ratios tell only part of the story.

As its name implies, a heat pump takes heat from an external source, such as air, and transfers it into a building. This enables a heat pump to have an efficiency greater than 100%, since more heat is delivered than the heat equivalent of the electricity consumed. Because of this higher efficiency, even with a purchased energy price ratio of about 3.8 to 1, the cost of delivering a unit of heat to a room by using an electric heat pump may be equal to, or even less than, that of delivering a unit of heat from a gas furnace.

Since gas deregulation, the price of gas has actually fallen somewhat and the electricity-to-gas price ratio has crept upward slightly. The use of such national price averages, however, obscures critical regional differences. Price ratios are much more favorable to electricity in the many parts of the country where energy for power generation is particularly inexpensive—as in the Northwest, with its hydroelectric resources. The electricity-gas price ratio currently ranges from a high of about 8 to 1 in Alaska, where gas is abundant, to nearly 1 to 1 in some parts of Washington state. In 1983 average-performance electric heat pumps could compete with conventional gas furnaces at price ratios up to about 3.8 to 1, except in the most severe climates.

But energy price is not the only factor affecting a homeowner's choice of heating equipment. Such considerations as equipment cost, safety, reliability, and convenience are also important. Among the trends that have most favored the installation of electric heating units, especially heat pumps, in new homes is the demographic shift toward sunbelt states. Electric heat pumps sell best where there are significant cooling requirements. In 1983 about three-quarters of new single-family houses were built in the South and West, where heat pumps accounted for 38% and 27% of the heating systems, respectively.

In other regions the convenience, low initial cost, and conservation potential of electric zoned heating systems—baseboard, panel, and radiant heaters—have become increasingly important. These systems have had their greatest penetration in the Northeast, where they are enabling homeowners to conserve energy during the harsh winters by heating only selected rooms. In 1983 such systems were installed in 20% of new homes in the Northeast. Noncentral electric systems have also been popular as retrofits in that region because of their ease of installation in older homes without air distribution ducts.

Focus on the heat pump

Much of the current attention being paid to the competition between gas and electricity for residential space heating has resulted from a spectacular rise in the sale of unitary electric heat pumps. (A unitary heat pump consists of one or more factory-assembled units designed for installation and use together, as opposed to separate components selected individually for field assembly. Unitary systems include both single-package and split-system models, the latter having some equipment outside a house and some inside.) The commercial sale of unitary heat pumps began in the 1950s but sputtered along at a fairly low level because of relatively high initial costs and some early reliability problems.

Early failures were corrected by improved designs and dealer training, but in 1974 annual sales of unitary heat pumps were still only about 139,000 units. Then, as a result of expected gas shortages, new residential gas hookups were suspended in many areas and the sale of electric space-heating equipment—particularly heat pumps—increased. Sales of electric systems were also spurred by the fact that power for such systems can reliably be derived from a variety of sources. Driven by falling electricity prices relative to those of gas, rising construction rates, and regional concerns over future gas prices and availability, annual shipments of heat pumps jumped to more than 572,000 units in just four years. Sales fluctuated somewhat during the recessions of the early 1980s, but by 1984 they had climbed to more than 745,000 units a year.

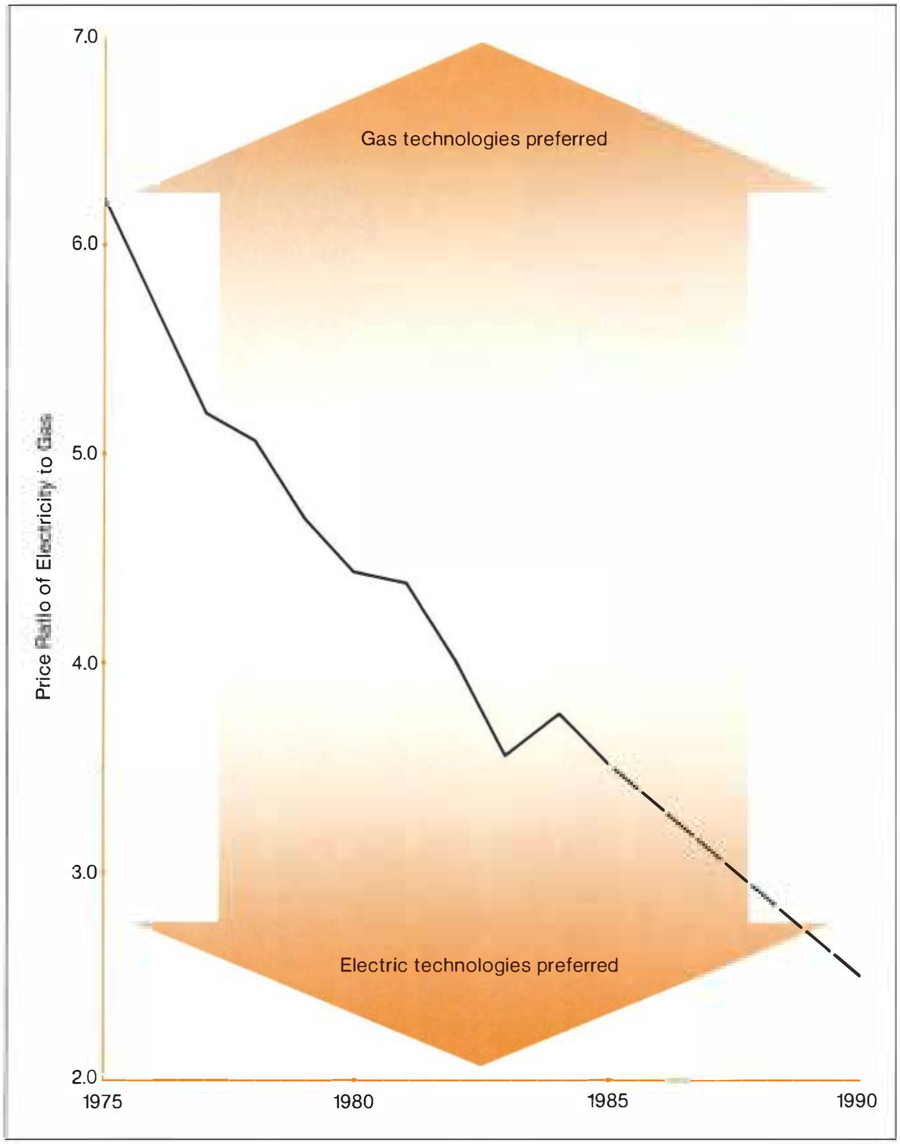
Although part of this growth resulted from the regulatory uncertainties surrounding the availability and cost of natural gas, additional impetus came from the active marketing of heat pumps by electric utilities. "Heat pumps respond to the three primary needs of the electric utility industry in the end-use area," says Orin Zimmerman, EPRI's technical director for energy utilization. "They help provide more efficient use of energy, better load management, and new opportunities for load growth."

Because heat pumps are much more efficient than other electric heating devices, for example, they can play an important role in utility efforts to conserve energy and defer capacity expansion. Heat pump efficiency also helps keep electricity competitive, and some utilities have offered incentives or special rates to customers who purchase high-performance models or upgrade heating equipment efficiency at replacement.

For utilities seeking to increase load growth, heat pumps can also provide an attractive way for customers to meet more of their energy needs by increasing household use of electricity. Cus-

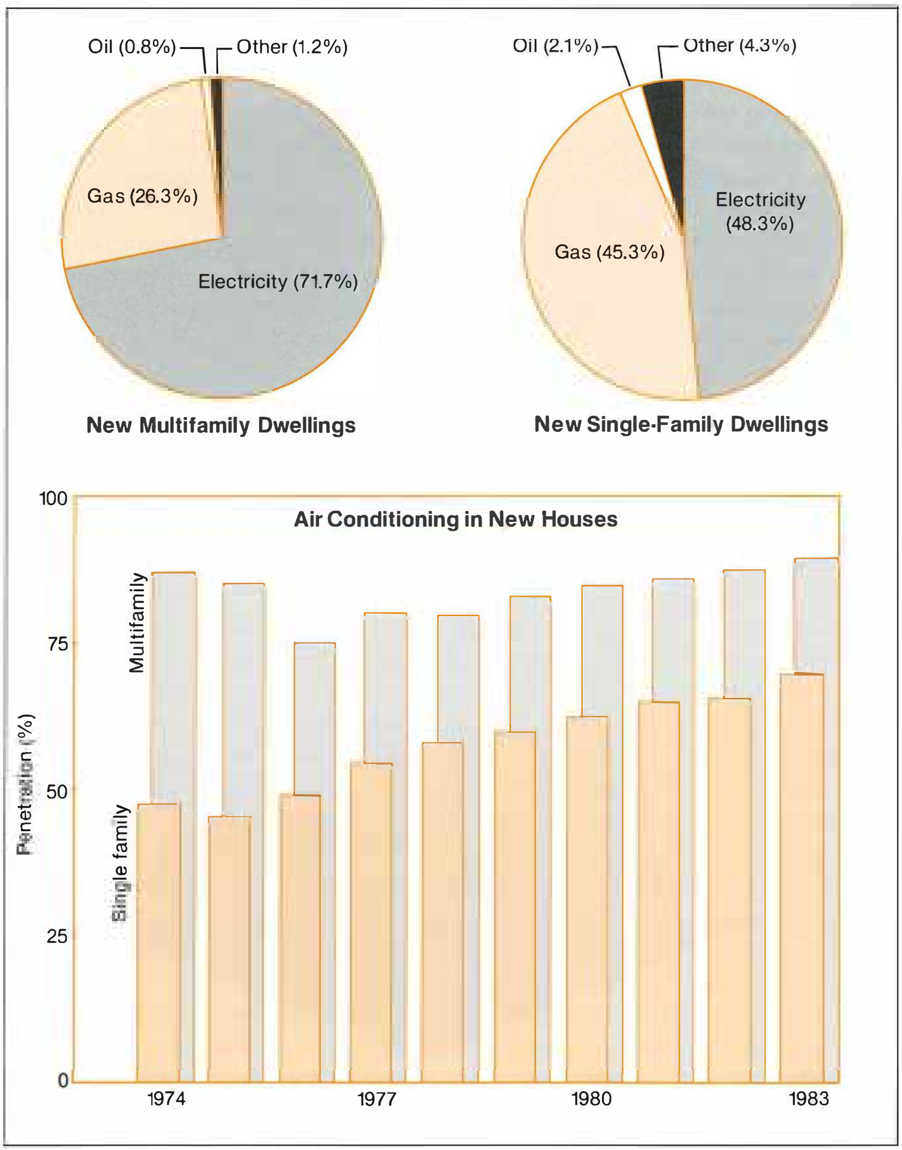
Electricity and Gas Price Trends

Historically, the greatest driving factor in the competition between gas and electricity has been their relative prices. The high "form value" of electricity, which allows nearly 100% of its energy to be employed effectively at the end use, makes it possible for electricity to compete with gas at a delivered cost ratio (based on \$/Btu) as high as 6 to 1 in specific applications. Relative prices have narrowed significantly in recent years, and electric heat pumps are now competing aggressively with gas furnaces at a fuel price ratio of about 3.6 to 1. If the relative price of electricity continues to decline, as projected by the Energy Information Administration, electric heat pumps will gain a significant advantage in the marketplace.



Sharing the Market

Although electricity now provides heating for only about 17% of existing homes in the United States, fuel choices being made for new homes imply a marked shift toward electricity in the future. In 1983 electric heating technologies were chosen for over two-thirds of new multifamily dwellings and for almost half of new single-family dwellings, with heat pumps accounting for about 30% of single-family purchases. The nation's increasing interest in comfort cooling is perhaps the greatest reason for this shift—air conditioning is served almost entirely by electric technologies, and at present the electric heat pump is the only device that can provide both heating and cooling from a single unit.



tomers who are building new houses are particularly good candidates for providing such load growth, since they may be able to avoid the cost of gas hookup completely by creating all-electric homes featuring heat pumps.

Another important benefit to utilities is seasonal load management. About two-thirds of EPRI member utilities experience their greatest load demands during the summer, largely because of the extensive use of air conditioners during hot weather. (About 70% of new single-family houses and 89% of new multifamily dwellings built in 1983 featured central air conditioning.) Because the size of a utility's generating capacity is often determined by such demand peaks, any measures that spread the load more evenly over a full year will help optimize the use of generating equipment. Heat pumps help such capacity utilization efforts by ensuring more electricity use during winter months. A family that buys a heat pump capable of meeting its summer cooling needs will then obtain most of its winter heating energy from electricity as well. Any additional energy needed on the coldest days can come from conventional resistance heating units or from dual gas-electric fuel systems.

For the gas utility industry, the rapidly expanding sales of electric heat pumps have presented a serious challenge. Taken together, electricity and gas account for about 92% of heating in new single-family houses and 98% of that in new multifamily dwellings. Thus each electric heat pump installed in a new house usually means that one less gas furnace will be sold.

In response to the rising challenge, critics within the gas industry have claimed that electric heat pumps have an operating life of only 7 to 10 years, that their lifetime costs are greater than those of gas furnaces, and that customers complain of increased draftiness with electric heat pumps. Despite maintenance problems with early models, a recent EPRI survey of Alabama Power Co. customers found that more than half of the heat pumps purchased 20 years ago are still operating and that most of the decisions made to change systems did not result from heat pump failure.The relative lifetime costs of a heat pump and a gas furnace will depend on a host of factors, says Arvo Lannus, the program manager for residential and commercial applications in EPRI's Energy Utilization and Conservation Technology Department; these include the efficiency of specific models, regional differences in energy rates, and patterns of use. As for the issue of draftiness, Lannus says, "A heat pump moves more air at a lower temperature than a furnace does. It's a different kind of sensation, but most people get used to it. You get some cool air at the startup of a gas furnace too."

The race for efficiency

Although the competition between gas and electric heating units for market share depends on many factors, such as perceptions of comfort and expectations of future energy prices, the competition in technological development is focused primarily on greater efficiency, higher reliability, and lower equipment costs. At GRI this research effort includes work both on high-efficiency gas furnaces and on several kinds of gas-fired heat pumps. At EPRI current development efforts center on designing an advanced generation of electric heat pumps whose performance characteristics will leapfrog improvements already being made in standard models.

For furnaces, efficiency is expressed as the percentage of energy consumed that is delivered as useful heat. A typical gas furnace currently installed has a seasonal average efficiency of 50–60%. One way to improve furnace efficiency is to provide an extra heat exchanger to remove more heat from combustion gases. An example of such an exchanger is the heat pipe—a sealed tube in which a working fluid is boiled at one end and condensed at the other. A heat pipe furnace with a seasonal efficiency of 85% has recently been developed by GRI to fill a gap in the residential heating market between the less efficient conventional gas furnaces and other, more expensive high-efficiency furnaces. It was introduced into the market in late 1983 by Borg-Warner Central Environmental Systems, Inc., under GRI license.

In the heat pipe furnace now commercially available, the moisture in flue gases does not condense. A higher-efficiency heat pipe furnace design based on the condensation of this moisture and the capture of its latent heat has now been developed as well. This version is expected to offer efficiency ratings of 90–95% and to be commercially available in the near future. Like other condensing furnaces, this advanced model will require corrosion-resistant materials because the condensed moisture of flue gases tends to be acidic.

A somewhat more effective, but more expensive, way to increase efficiency is to improve the transfer of heat during combustion, in addition to condensing moisture in the flue. In a pulse combustion furnace, a gas-air mixture is ignited by a spark plug in a series of pulses—up to 63 per second—that create enough pressure to momentarily close inlet valves and expel the exhaust gases with a puff. This process is highly turbulent, which improves combustion efficiency and increases the transfer of heat from the combustion chamber. Another advantage of the pulse combustion furnace is that it can operate at lower combustion temperatures and with reduced air input, thus producing less nitrogen oxide emission.

The problem with pulse combustion, which was conceptually derived from the ramjet engine, is its noise. Thus the challenge for GRI researchers has been to develop pulse combustion units that are both quiet and compact enough for home use but still competitively priced. One pulse combustion furnace, designed for central heating systems and offering 96% steady-state efficiency, was introduced commercially in late 1981 by Lennox Industries, Inc., under license from GRI. Coming along next is a smaller pulse combustion unit, designed for heating individual rooms and tested at more than 93% efficiency (compared with efficiencies of only 45–65% for conventional gas space heaters). The unit is designed to meet residential space-heating needs while helping homeowners avoid the costs of expensive venting systems.

The concept of efficiency is more complicated for the heat pump, since it delivers more useful energy than is input as electricity and thus can be said to have an efficiency greater than 100%. To avoid confusion engineers have adopted an alternative measure called the coefficient of performance, or COP. The COP of a heat pump is defined as its heat output divided by the amount of electricity used—both expressed in the same units, so that COP is dimensionless. Electric heat pumps with a seasonal average COP of 2.6 are now commercially available, but more typical models have a seasonal average COP closer to 2.0. (Such seasonal COPs are usually calculated for a climate like that of Pittsburgh; actual seasonal COPs in other locations may be higher or lower.)

As energy conservation efforts have gained momentum, more precise ways have been sought to express seasonal averages of heat pump performance. These new measures are determined for a specific set of operating conditions and consider the heating and cooling cycles separately. Cooling performance is now commonly expressed as a seasonal energy efficiency ratio (SEER); to calculate this value, the total heat (in Btu) removed by a unit during a season under specified conditions is divided by the total electric energy consumed (in watthours). The 1983 average SEER for electric heat pumps was about 8.2 Btu/Wh. For heating, the comparable term is heating seasonal performance factor (HSPF), which is also defined in terms of total energy delivered and consumed under specified conditions. The 1983 average HSPF for electric heat pumps was 6.4 Btu/Wh. (Either figure can be converted to an equivalent seasonal COP by dividing it by 3.413 Btu/Wh.)

The average SEER of commercially available heat pumps has been increasing steadily by about 2.5% a year. To accelerate the introduction of more efficient heat pump technology, EPRI is sponsoring the development of an advanced heat pump intended to provide a significant step in performance when it goes on the market about 1990. Performance targets include an HSPF of 10.4 Btu/Wh and an SEER of 14 Btu/Wh. The unit is also being designed to offer improved load characteristics to utilities, to have lower outdoor sound levels, and to provide improved reliability. Now being developed by Carrier Corp., the advanced heat pump is expected to be ready for field trials in 1988.

Although technical details of the Carrier project remain proprietary, EPRI and equipment manufacturers have been considering a variety of ways to improve heat pump design. One method for raising the operating COP of a heat pump is to improve the performance of its individual components. Another is to use a microprocessor-based thermostat to optimize operation. Such controls will enable a heat pump to modify its operation to achieve the highest performance for a given set of conditions. For example, the internal refrigerant flow of a heat pump could be regulated to achieve peak efficiency. Unit cycling could also be reduced by using a variable-speed motor to drive the heat pump, rather than making it continually turn off and on.

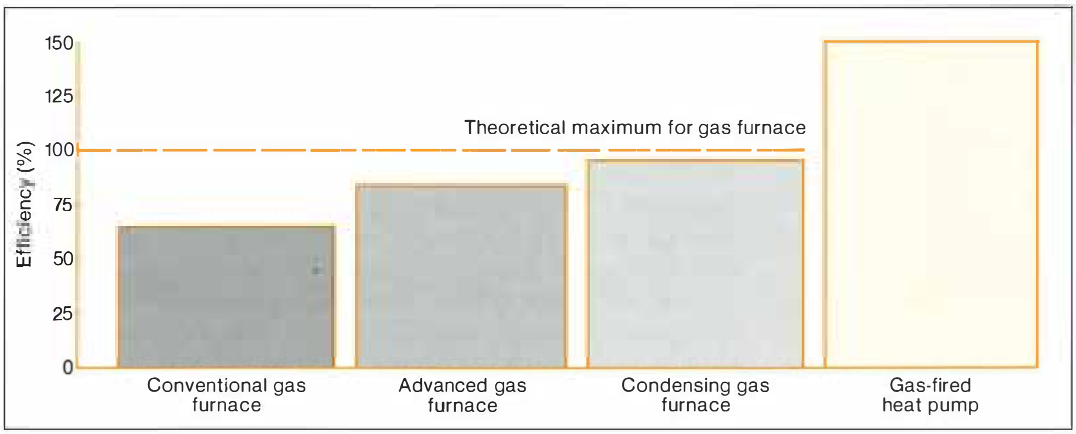
Improved compressor designs, both to increase efficiency and to reduce the number of maintenance problems, have gained particular attention. A supercharged reciprocating compressor with an economizer cycle can improve seasonal performance by up to 21% over conventional designs, depending on climate. A rolling-piston rotary compressor, which is cheaper and has fewer valves and total moving parts than a reciprocating compressor, has been used extensively in Japan (and in the United States in small sizes) and is being modified for use with a variable-speed motor. A scroll-type compressor is capable of providing high efficiency in a valveless design over a wide range of operating conditions and holds promise for application in central heating and cooling systems for homes. The screw compressor was once limited to large commercial refrigeration units, but as costs come down, it may be used in heat pump systems in multifamily dwellings or, eventually, even in single-family homes. Centrifugal compressors, which operate like turbines, can be used for the largest heat pump applications.

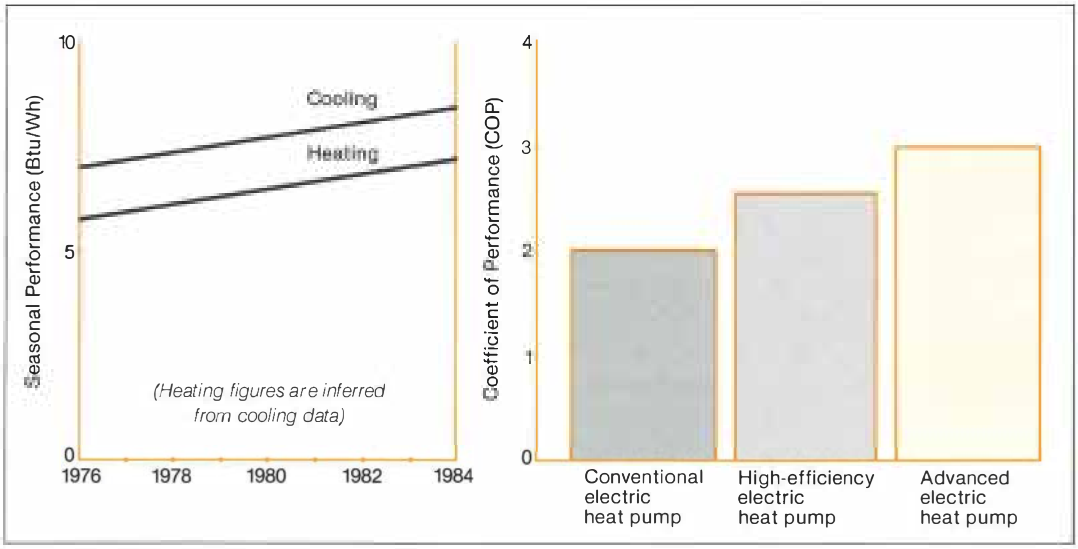
Toward a gas-fired heat pump

At about the same time that EPRI's advanced electric heat pump is scheduled for market introduction—1990—GRI anticipates the commercialization of its first residential gas-fired heat pumps. To achieve this goal, GRI is seeking substantial federal funding as part of a cooperative research program with the U.S. Department of Energy (DOE). GRI is budgeting more than $13 million for next year to continue investigating several concepts for both residential and commercial gas-fired heat pumps, and it recently requested Congress to increase DOE support of the cooperative program from $4.5 million in FY85 to $11.0 million in FY86. This program has been in development for three years, with GRI concentrating most of its funds on systems development and DOE committing more than half its funds to supporting research, systems analysis, and the evaluation of new concepts.

The Gas Contenders

Competition has spurred the development of gas furnaces with higher and higher efficiencies. Conventional units, which still heavily dominate the residential heating load, have an efficiency of about 65%. Advanced furnaces and condensing furnaces bring this figure up very close to the theoretical maximum of 100%. To go beyond this ceiling, gas researchers are turning to development of a completely new technology, the gas heat pump. This is the central thrust of current work sponsored by the Gas Research Institute.



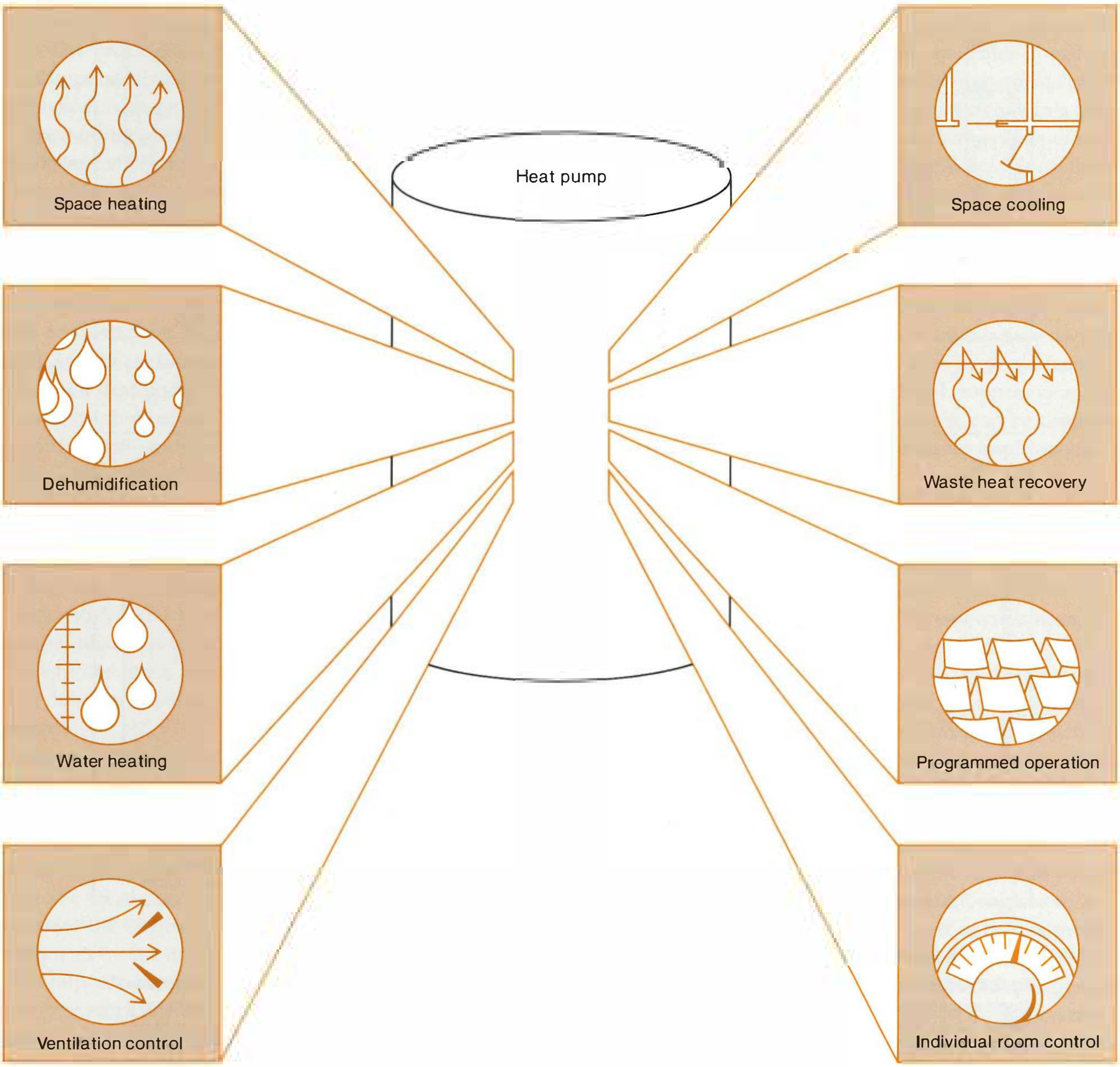


Electric Heat Pump Efficiency

Performance figures for electric heat pumps have risen at a steady rate of about 2.5% a year over the last decade. Commercially available units are now operating at seasonal average heating COPs as high as 2.6, and the current target for near-term advanced devices is 3.0. Even with such advances on the drawing board, electric heat pumps still have plenty of headroom for future efficiency improvements because current heat pumps are rated at only about 20% of theoretical maximum efficiency.

System of the Future

The residential energy system of the future will incorporate many functions now served by individual devices into one central environmental conditioning and control unit. The flexibility and high efficiency of the heat pump make it a natural core technology for such a system.



As with EPRI and its advanced electric heat pump, GRI has set ambitious performance targets for gas-fired heat pumps. Initial units are expected to have a seasonal average heating COP of at least 1.25 and a seasonal average cooling COP of at least 0.80. Second-generation units are to have a seasonal average heating COP of at least 1.5 and a seasonal average cooling COP of at least 1.0. (Direct comparison of the performance factors of gas and electric heat pumps is difficult because gas is a primary fuel, actually burned inside the unit.) Another key target for the new gas-fired heat pumps is the expected service life of 10–15 years. Because GRI expects the initial cost of gas-fired heat pumps to be 25–60% higher than other space-conditioning options, their cost-effectiveness will remain very sensitive to performance and to variation in gas and electricity prices.

Two of the gas-fired heat pumps being developed by GRI have chemical heat-absorption cycles rather than a compression cycle, and so differ fundamentally from electric heat pumps. One of these designs has a single-effect absorption cycle in which heat from burning gas is used to boil a refrigerant out of solution in a generator vessel; the resulting vapor is forced through a heat exchanger, where it cools and condenses. The other design, which has a double-effect absorption cycle, works on the same basic principle but has two generators.

The other three types of gas-fired heat pump receiving GRI support all use an engine to drive a compressor. One design employs a gas-fired, reciprocating internal combustion engine; another uses a rotary internal-combustion engine; the third uses an external-combustion, free-piston Stirling engine. The potential advantage of the Stirling engine is that it can operate more efficiently, but it will also probably be more expensive and require more extensive development.

The importance the gas industry attaches to these efforts was expressed succinctly in GRI's strategy document for its space-conditioning program: "GRI believes that the residential gas heat pump is the next giant step in advanced gas space-conditioning equipment that will keep natural gas as the fuel of choice for heating and establish natural gas as a competitive fuel for cooling well into the 21st century."

Other members of the technical community are not so sanguine. "There's no question that the gas industry has committed a great deal of money and effort to developing a commercially viable gas-fired heat pump," says James Calm, EPRI's project manager for heat pump development, "but it faces major hurdles in each of its designs. These devices will be expensive to fabricate, and it is still too early to say whether a gas-fired heat pump will ever become commercially successful. Meanwhile, gas furnace technology is approaching its theoretical efficiency limit of 100%. The electric heat pump, on the other hand, has reached only about 15–20% of its theoretical limit, leaving much room for improvement."

A glimpse at the future

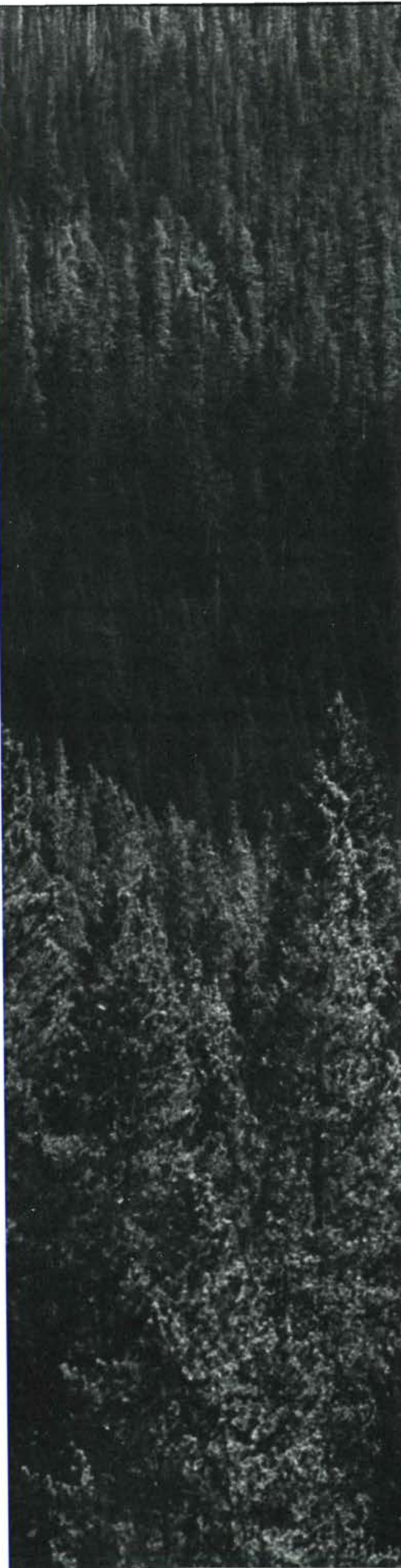
Beyond the specific projects just described, a wide variety of other devices may also play important roles in the ongoing competition between gas and electricity for shares of the residential energy market. Heat pumps that use the ground or groundwater as a heat source—rather than air—may help open new residential space-heating markets in colder climates, since ground temperatures tend to be more moderate than air temperatures. Window- and wall-mounted heat pumps, which are also becoming available, will allow homeowners to condition one room at a time. Another way to achieve the same end is to use a multizone heat pump, which couples a single outdoor compressor and heat exchanger to several fan coils inside a house. Also, the electric heat pump water heater may be used increasingly to meet most of a home's hot water needs, although it may require a larger storage tank because it has a somewhat slower recovery rate than conventional models.

"For every price of gas and electricity, there will be a portfolio of equipment that can provide maximum service to customers," says Thomas Schneider, the director of EPRI's Energy Utilization and Conservation Technology Department. "Both gas and electric technologies have their place, and when conditions change, another new set of equipment can be developed for each energy source." Overall fuel costs will probably continue to rise, Schneider says, but "through new technology, tighter homes, and continuing conservation programs, we have the capability of reducing residential energy consumed for space conditioning to less than half the level of the 1960s. Ultimately that will work to the advantage of everyone—homeowners, utilities, and the nation." ■

This article was written by John Douglas, science writer. Technical background information was provided by Arvo Lannus, James Calm, and Orin Zimmerman, Energy Management and Utilization Division.

Forest Stress and Acid Rain

Scientists are attempting to define the web of causation behind the decline of forest stands in Europe and America. Most agree that a combination of stresses are responsible, and researchers are looking closely at disruptions to fundamental nutrient cycles.



Hundreds of scientists are searching mountaintops and watersheds from Germany and Scandinavia west to California's Sierra Nevada, looking for clues to explain recent forest decline. They are finding discolored leaves and slowed growth in some places; elsewhere, individual stands of trees are dying. Data from dozens of studies are slowly being assembled to reveal a picture of what is happening to the forests—and why.

The story began in Stockholm at the 1972 United Nations Conference on the Human Environment, where Sweden and Norway drew worldwide attention to the acidification of lakes and streams in Scandinavia and the decline of fish populations in these waters. In the mid 1970s, similar phenomena were reported for high-elevation lakes in the Adirondack Mountains of New York. As concern over aquatic systems continued, scientists began noticing signs of decline in forests. At first they found little to be concerned about. In recent years, however, the situation has grown more troublesome.

Warning signals

Tom Siccama was a forestry student when he surveyed the vegetation on Vermont's Camel's Hump Mountain in 1964. In 1979 he and co-workers from Yale University repeated the survey and found some disturbing evidence. Over half of the red spruce on Camel's Hump had inexplicably died in the 15 years since Siccama had first walked the mountain. In addition, many of the live trees were in various stages of decline. Siccama's findings stimulated further field surveys, which revealed that the red spruce—from young saplings to 300-year-old veterans—are dying in some of the high-elevation forests of Vermont, northern New York, and New Hampshire.

The process of decline is readily visible. The trees initially lose foliage at their tops and branch tips. This process moves down the trunk and inward over time, stripping needles from the branches. Photos of New England's affected areas taken in the early 1960s show lush, healthy stands. Some of these sites now show clear signs of decline.

After hearing about the decline of red spruce in New England, Dr. Robert Bruck of North Carolina State University began to study the spruce-fir forests of the southern Appalachians. During 1983 and 1984 he and his graduate students gathered detailed information from plots on Mt. Mitchell and seven other mountains in the region. Their preliminary findings suggest a decline among red spruce similar to, though not as severe as, that in New England. Bruck's group believes that the decline is most severe on high-elevation windward slopes, which are exposed to higher levels of anthropogenic (man-made) pollution than leeward slopes.

Meanwhile, across the Atlantic in West Germany, *Waldsterben*—forest death—has become an emotionally and politically charged issue. A 1983 poll indicated that West Germans were more worried about the condition of their forests than about the then-imminent deployment of Pershing missiles on their soil. "Americans do not understand the almost mythical role that forests play in the German consciousness," explains John Huckabee, manager of EPRI's Ecological Studies Program. Germans revere their forests, which are among the most carefully tended in the world. Now that the forests are threatened, the people—and the government—are very upset.

Much of the concern in West Germany was kindled in 1982 by the results of a federal government questionnaire sent to corporate, private, and governmental forest associations. The survey indicated that 8% of the country's 7.4 million hectares of forest contained trees in some stage of decline, from slight needle loss to severe damage. This disturbing finding prompted the government to conduct its own survey the following year, and it established representative plots. Foresters cruised the woodlots and categorized sample trees as slightly to severely damaged on the basis of visual criteria that included yellowing and early loss of needles, deformed shoots, deteriorating roots, and progressive thinning of tree crowns.

The 1983 survey found that 34% of the forested area showed some signs of decline. Problems were found at all elevations, among young and old trees of various species in a wide range of forest types. Within a year, the problem had reportedly increased: over 50% of the forested area exhibited some symptoms of decline.

West Germany is not alone. Less well documented reports from Czechoslovakia, Poland, East Germany, Romania, Switzerland, Austria, Yugoslavia, Italy, France, Sweden, and Norway indicate varying degrees of forest decline might be affecting other regions of Europe.

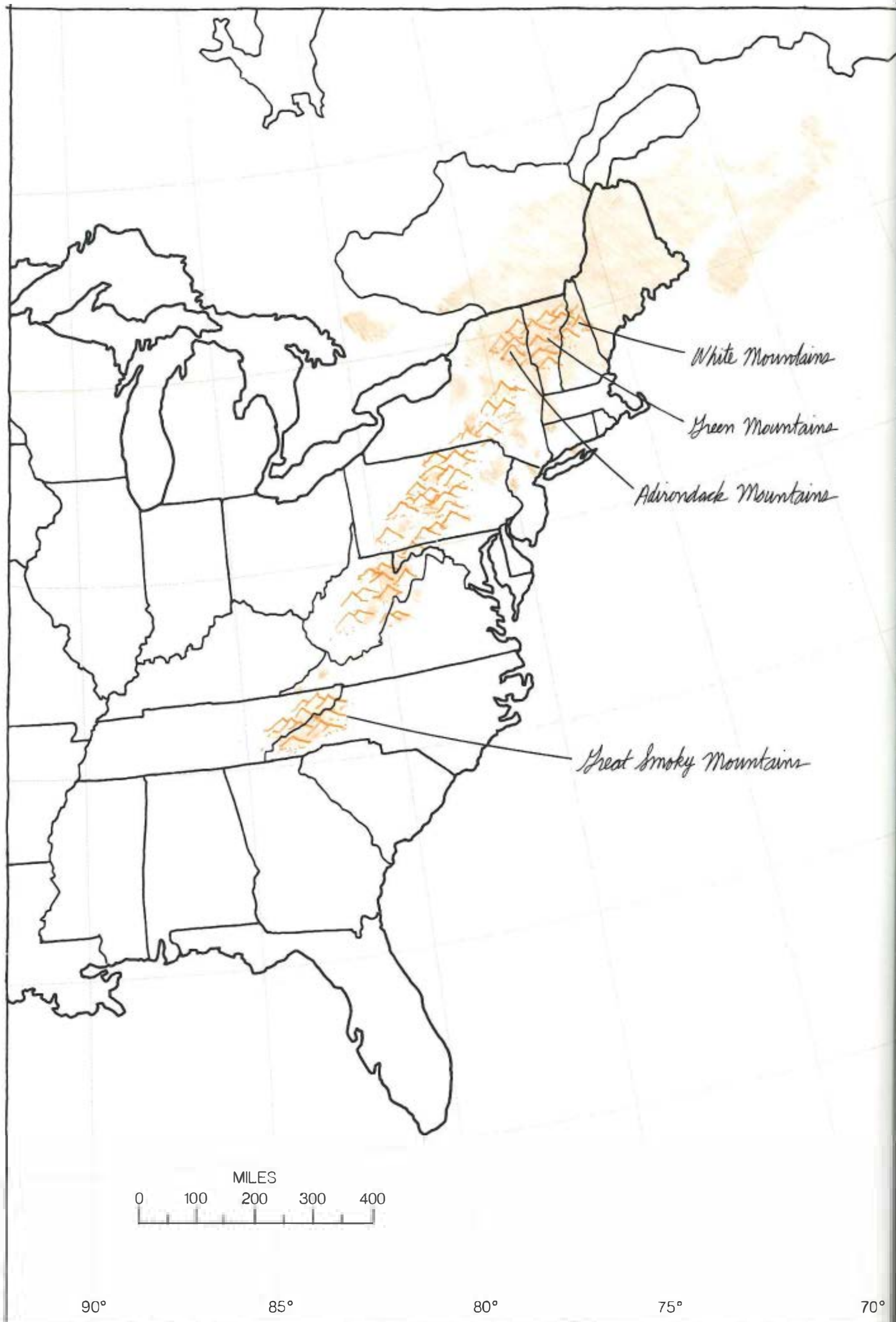
Sorting it out

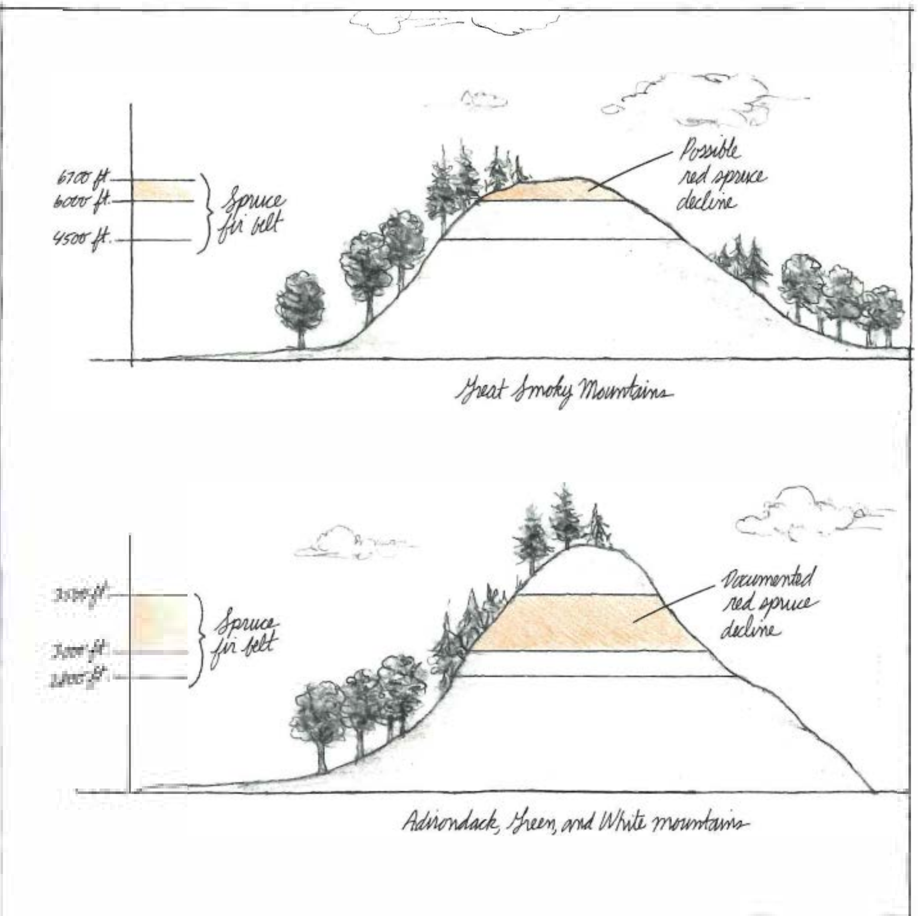
What are we to make of these reports? John Huckabee states that there is strong agreement in the scientific community that red spruce are declining in North America and that there are real, unexplained problems in the German forests. Beyond this, there is little consensus. Huckabee notes that the announcements of disaster abounding in the press are seldom supported by documented evidence of forest decline in peer-reviewed scientific journals. "The plural of anecdote," he cautions, "is not data."

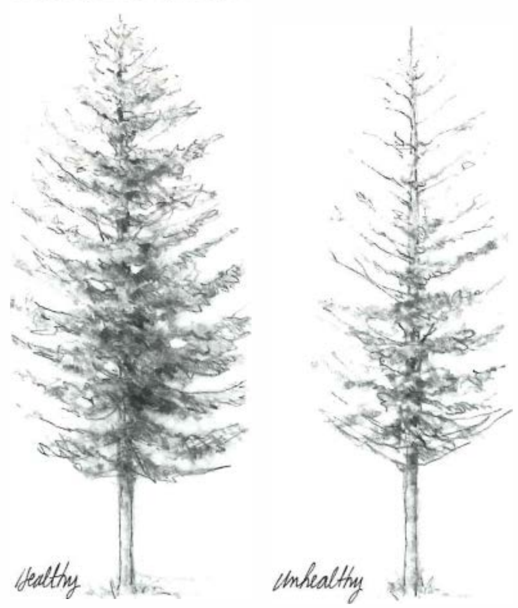
Furthermore, data can be presented in ways that are easily misunderstood. In the 1983 and 1984 German forest surveys, two-thirds of the affected trees were in the "slightly damaged" category, whereas less than 2% were severely damaged or dead. This distinction is obscured when data are aggregated into figures for overall decline, and an exaggerated impression of the damage can result. "There's no question that the German forests are hurting badly," asserts Robert Bruck, "but there's also little doubt that politics played a role in the design of the study."

Geography and Symptoms of Decline in Red Spruce

Red spruce is the only North American tree species suspected of experiencing pollution-related decline. The decline appears in a small portion of the tree's range—high in the Green, White, and Adirondack mountains of Vermont, New Hampshire, and New York, and possibly in high-elevation stands in the Great Smoky Mountains of western North Carolina. Red spruce (shaded area) grows from the Canadian maritimes across southern Ontario and Quebec, then south through the mountains of New England, upstate New York, and the Appalachians. It is found near sea level in the northern portion of its range and at progressively higher elevations in the southern reaches of its habitat.







In the areas experiencing decline, red spruce of all ages are affected. The decline begins with discoloration, followed by loss of needles progressing from the top of the tree down and inward from branch tips toward the trunk.

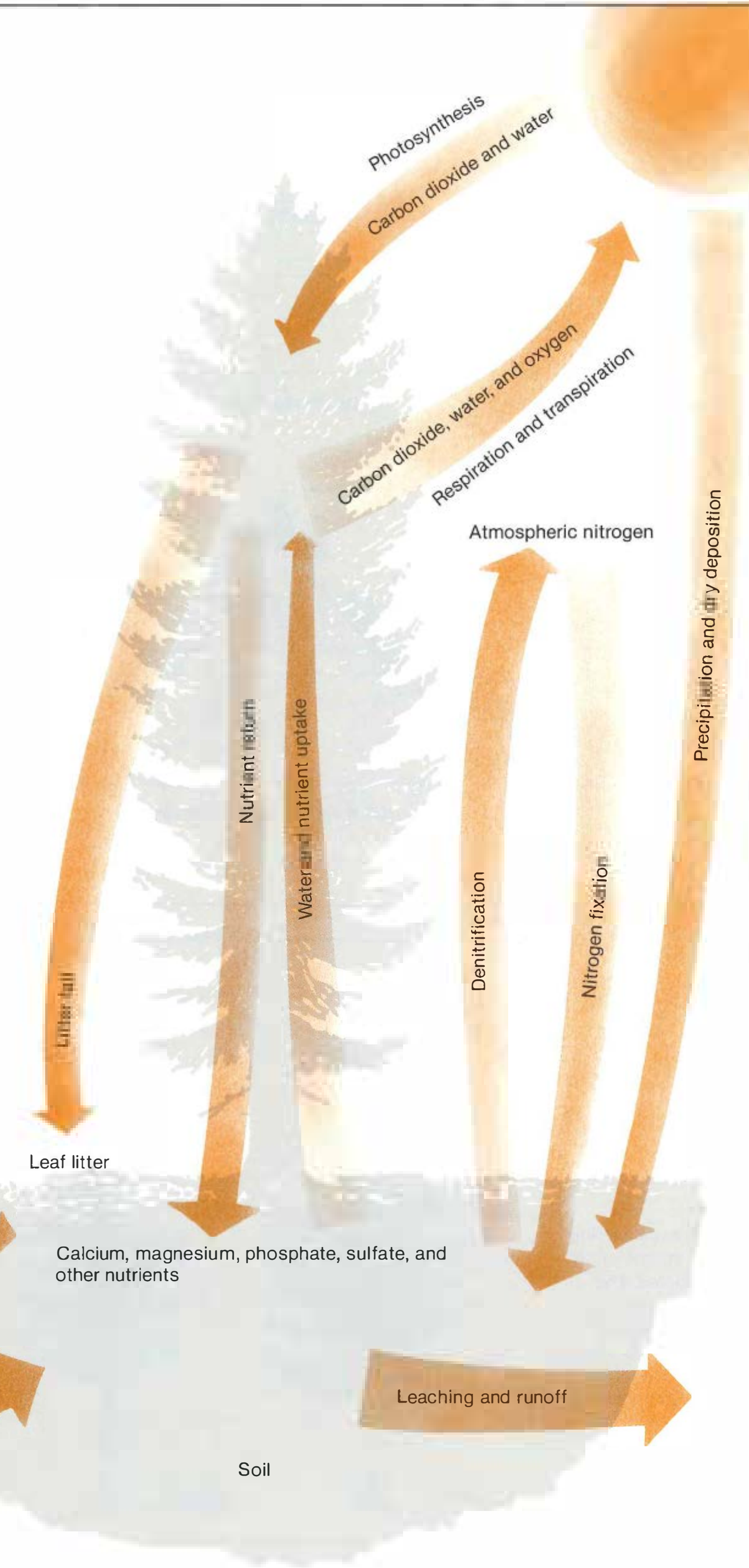
Bruck claims that the Germans are so upset about their trees that they are grabbing at any straw that might offer relief. "One week after it was suggested that nitrogen, rather than sulfur, might be worth looking at, signs appeared on the autobahn saying 'Slow down to save the trees.' " (Much of the nitrogen contained in air pollution comes from cars.) "It's like a pollutant-of-the-week award," says Bruck.

There are problems with some of the American research on forest decline as well. For instance, a major government-sponsored study known as FORAST (forest response to anthropogenic stress) sent researchers into the woods in 15 eastern states from Maine to Arkansas to gather 14,000 core samples from 31 tree species. Dendrochronological analysis of the cores led to initial reports of widespread growth suppression throughout the range of the study. Problems with sampling techniques and data analysis, however, have raised serious doubts about the validity of the interpretations. As Huckabee points out, "Examination of growth rings can tell us how fast a tree was growing during a certain period, but it can't tell us why."

According to some in the environmental community, the German experience suggests that forest decline can move so fast that if we wait for uncontroverted evidence to emerge that our forests are endangered by pollutants, any remedial actions we take may come too late. Others argue that to prevent or remedy forest decline we must understand its causes and mechanisms. "It's not enough to do correlative studies that treat the forest as a black box and simply attribute its symptoms to certain measured inputs," claims EPRI Project Manager Robert Goldstein. "There are so many interactive factors that influence forests—climate extremes, elevation, soil characteristics, nutrient and water availability, competing plants or pathogens, pollutants, and many others—that it is difficult to draw broad conclusions from correlational techniques. Without

Nutrient Cycling in a Forest Ecosystem

A complex web of energy and nutrient cycles sustains the health of forests. Plants obtain nutrients from atmospheric gases, dry and wet deposition, ground and surface water, and from the decomposition of organic matter and bedrock in the soil. These nutrients are continually being absorbed and released by plants and changing form as they move among compartments of the ecosystem. In the nitrogen cycle, for example, free atmospheric nitrogen is fixed by soil bacteria into molecular forms, such as ammonia and nitrate, that plants can absorb through their roots. In the carbon-oxygen-hydrogen cycle, photosynthesis converts sunlight, carbon dioxide, and water into stored energy in the form of glucose. Respiration—the opposite of photosynthesis—breaks down some of the glucose to release energy, which fuels the metabolic processes that keep plants alive. Leaves and branches fall to the ground, decompose, and release nutrients that are reabsorbed from the soil through the plants' roots. EPRI's forest effects research focuses on understanding these and other cycles, the ways in which the cycles are disrupted by such stresses as pollution, and the effects such disruptions have on ecosystem health.



an understanding of what's going on inside the system, one has no idea how all these factors are interacting."

Goldstein and his colleagues at EPRI have been supporting research aimed at revealing the mechanisms of forest decline. They study nutrient cycling and other processes within ecosystems and then try to learn how various stresses alter these flows. "It seems more complicated than correlational methods," says Goldstein, "but the mechanistic approach is actually a simpler and more elegant way of understanding the forests."

Most scientists believe that varying combinations of stresses, rather than any one agent, are responsible for forest decline. Unraveling this complexity is difficult, and we may never find clear-cut links between cause and effect. As one researcher puts it, "Those waiting for science to come up with a magic cure to forest decline are going to be very disappointed." Scientists have narrowed the field, however, to a handful of the most likely stresses, which could work together—in different ways at different sites—to cause most of the forest decline now occurring.

Climate changes and extremes, natural ecological succession, pests and pathogens, management practices, and various pollutants are all implicated. The late 1950s and early-to-mid 1960s was a period of drought in the northeastern United States. Some scientists believe that drought-induced stress could have weakened red spruce in the Northeast, making them more vulnerable to pollutants and other stresses. The decline of red spruce at Mt. Mitchell and other southern Appalachian sites, however, cannot be attributed to drought. Precipitation data show that at no time since 1930 has there been a drought on Mt. Mitchell. Still, climatic factors other than drought may be involved. The most pronounced instances of forest decline in the eastern United States are on mountaintops, where weather is severe and soils, typically, are thin. The climate extremes in these locations may be a key factor in making the forests vulnerable to other stresses, which they might better endure in more sheltered sites.

Management practices such as overharvesting and planting of species outside their natural range (as with Norway spruce) may be part of the problem in Germany's forests. These forests have been intensively managed for centuries. The removal of fallen branches and leaf litter from the forest floor over many generations may have affected the supply and cycling of important nutrients. Nutrient sources vary from area to area, however, and some old, intensively managed European forests exhibit no signs of decline.

Focus on air pollution

Of all the possible causes for unexplained forest decline, air pollution is the most hotly debated. Various pollutants are mentioned, but the current leading hypotheses concern acidic deposition, ozone, and, to a lesser extent, heavy metals. Acid rain is just one form of acidic deposition, a category that also includes deposition from fog or mist and dry deposition of acid precursors (materials that will form acids when they interact with water). These acids, principally sulfuric and nitric, are the result of atmospheric chemical reactions involving oxides of sulfur and nitrogen produced naturally and in the combustion of fossil fuels—in vehicles, factories, and power plants.

Although acid rain has received a great deal of media attention, the impact of acid mist may be far more important in some instances, such as the dieback of red spruce at high elevations. High peaks in New England, the Adirondacks, and the southern Appalachians are shrouded in clouds much of the year. Monitoring has shown that clouds can concentrate pollutants so effectively that they are often 10 times as acidic as rainfall at the same site.

Scientists do not yet understand how acidic deposition might be harming forests, but several hypotheses are the subject of intensive research. Professor Bernhard Prinz of the Air Pollution Research Institute in Essen, West Germany, postulates that the combined effect of ozone and acid mist is causing much of the damage to German forests. One suggested mechanism is that ozone causes the stomates—gas exchange pores in the leaves—to stay open wider and for longer periods than they typically do; thus, acids are able to enter the interior of the leaves, where they leach out nutrients and cause tissue damage.

The aluminum mobilization hypothesis suggests that acidic deposition increases the acidity of forest soils, converting aluminum—which is bound tightly to soil particles in higher-pH (less acidic) soils—into a soluble form readily absorbed by plant roots. Aluminum toxicity might then damage the roots, leading to harm elsewhere in the tree. An EPRI-sponsored study is now testing this hypothesis by examining the way aluminum cycles through forest watersheds and the role it plays in the ecosystem. Many scientists are skeptical about the aluminum hypothesis and other theories based on the notion that acid rain initiates damage by lowering the pH of forest soils, because most forest soils are naturally quite acidic. Soils in the spruce-fir forests of North Carolina, for instance, typically range in pH from 3.2 to 3.5.

There are other possible mechanisms by which acidic deposition could affect forests. The depletion of calcium, magnesium, and other nutrients by leaching, either from the foliage directly or from the soil, has been considered. In microcosm studies sponsored by EPRI and other institutions, plants were exposed in control chambers to simulated acid rain. None of these studies has yet shown that acid precipitation at ambient levels has any significant impact on nutrient levels in the plants, affects the decomposition of organic matter in leaf litter and soil, or causes any physiological or morphological harm.

There are limitations to the microcosm approach, however. Such studies are relatively short-term, for instance, because trees soon outgrow their chambers. It is possible that more significant effects would arise from longer exposure to acid rain. Recognizing the limitations of microcosm studies, EPRI is also funding several field studies on the effects of acidic deposition on forests. One compares the atmospheric levels of acidic pollutants with deposition levels and runoff from the forest canopy. This study will provide important insights into the effects of acidic deposition on nutrient levels and cycling in leaves and on the manner in which precipitation is altered as it passes through the canopy and runs down stems, branches, and trunks to the ground.

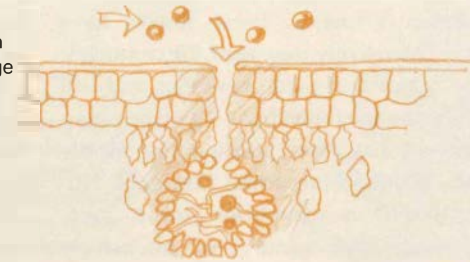
Another EPRI-sponsored study is developing a model to quantify the pools and flows of nitrogen in forested watersheds. The model—due to be completed in 1985—will be a valuable tool for understanding the ecological effects of nitrogen deposition. The nitrogen model study is very timely: according to a recently proposed hypothesis that is receiving a lot of attention, one cause of forest decline may be that we are, in effect, overfertilizing the forests with nitrogen.

Dr. Arthur Johnson of the University of Pennsylvania has studied New England forest decline since the late 1970s. He states that "there apparently is more nitrogen going into the high elevation forests of New England than the forests can use" and that "the rates of nitrogen deposition at these sites are higher than those at lower elevations in the same region and are extremely high compared with those in remote areas." Johnson explains that there is some evidence that an increase in nitrogen can reduce winter hardiness and frost tolerance in trees. One possible mechanism is that trees exposed to excess nitrogen do not "harden off" as soon as they need to in preparation for winter. If they grow on mountaintops where severe storms come early, they may be more susceptible to frost damage.

Leading Hypotheses of Forest Decline

Scientists are investigating and debating dozens of hypotheses on the causes of unexplained forest decline in North America and Europe. Some of the leading ideas are described below. It is likely that no single hypothesis is correct in all instances. Rather, problems in different areas may well be caused by unique combinations of factors.

Ozone-acid mist: Elevated ozone levels in the lower atmosphere cause gas exchange pores in the leaves to open wider and for longer periods than is typical. Acidic mist enters the leaf through the open pores (shown), damages tissues, and disrupts photosynthesis and other metabolic functions inside the leaf.



Nitrogen overfertilization: Atmospheric deposition of nitrogen from anthropogenic (man-made) sources overloads the ecosystem with this important nutrient. Trees respond by allocating carbon to new growth later into the season than is normal, reducing winter hardiness and increasing vulnerability to frost damage.

Soil acidification: Acidic deposition increases the acidity of forest soils, leaching out some nutrients and converting aluminum in the soil from insoluble to soluble form. Root hairs absorb and are damaged by the soluble aluminum. Damage to roots impairs water and nutrient uptake by the tree.

Direct foliar damage: Acidic deposition erodes the waxy, protective layer on the outside of leaves (shown), leaches out nutrients, and increases vulnerability to pests and disease.

General stress: Varying combinations of climate extremes, pests and pathogens, and other natural stresses in concert with one or more of the anthropogenic factors described above are responsible for the unexplained forest decline now occurring.

What does a healthy tree look like? The answer seems obvious at first, but this seemingly easy question has foresters stumped. In any forest one finds trees in varying states of vigor or decline. Some are weakened by frost, wind, or drought. Others may be stunted by shading from a taller neighbor. Typically, even the healthiest of trees bears the mark of one stress or another. In measuring the extent of newly discovered forest decline, scientists are having difficulty agreeing on where the range of normal symptoms ends and the early signs of illness begin.

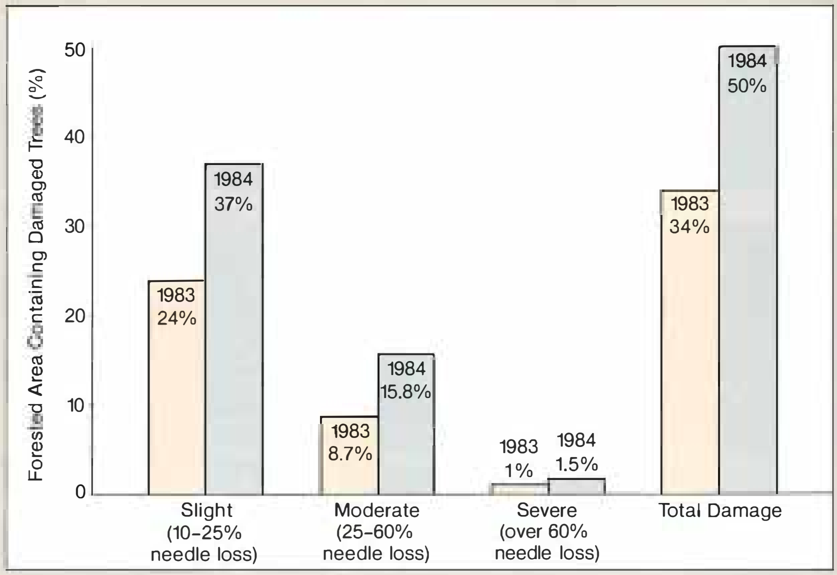
In West Germany foresters used needle loss as their primary criterion in measuring tree health during the 1983 and 1984 forest surveys.They called trees with less than 10% needle loss healthy and characterized those with more than 10% loss as either slightly, moderately, or severely damaged, depending on the degree of defoliation. The Swedes look at things differently. They feel that normal, healthy forests will have some trees missing up to 20% of their needles. Thus, when they conducted a national forest survey in 1984, they looked for the same symptoms as the Germans but counted as healthy all trees with less than 20% needle loss.

The Germans report that their forest decline rose from 34% in 1983 to 50% in 1984. Two-thirds of the damage, however, was what the Germans termed "slight" damage (10–25% needle loss). According to German researcher Dr. Lutz Blank, if his countrymen had used the Swedish damage classification in their 1984 survey, "the figure of 50% damage would have collapsed to about 17%."

Even 17% damage is significant enough to leave little doubt that unexplained forest decline is occurring in West Germany, but that assessment is far less dramatic than the claim that half the German forest is ill. This example illustrates that methodological details that might appear trivial can have a profound influence on our perception of what is happening in the forests. As time goes on and more surveys are conducted, scientists will be striving to agree on consistent ways of identifying and categorizing forest damage. Without such consistency, it is difficult to compare damage figures from one year to the next or from one country to another. Students of forest decline must be aware of this subtlety and must learn to look behind the numbers to see how the manner in which they are obtained influences the final tally. □

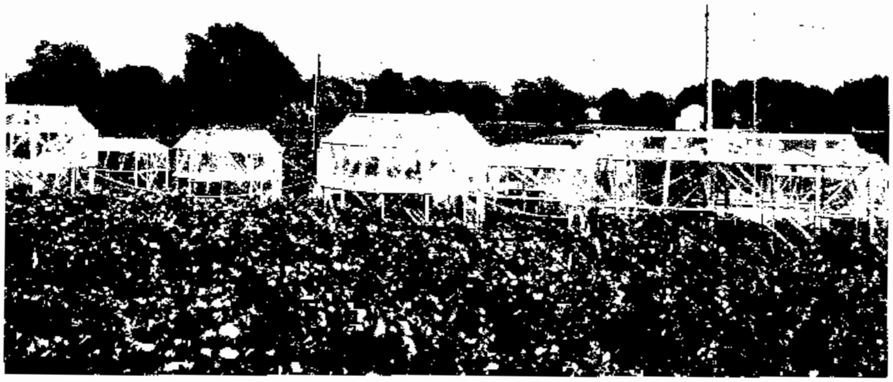
Tree Damage in West German Forests

Measuring forest decline is difficult, and the results obtained in forest assessment depend in large part on the survey methods and criteria. In both the 1983 and 1984 West German forest surveys, the damage identified as "slight" (10-25% needle loss) makes by far the largest contribution to the assesssment of total damage. Had these surveys used the Swedish criteria, which consider a tree with up to 20% needle loss as being undamaged, the bars indicating slight and total damage would have been much smaller.



Forest Effects Research

Scientists conduct both field and laboratory studies to learn about the response of forests to such stresses as pollution. Microcosm chambers allow researchers to mimic natural conditions while varying certain specified parameters, such as the acidity of precipitation. Field studies measure changing conditions in stream runoff, soils, and other compartments of the natural ecosystem.



Johnson believes that nitrogen's potential role in forest decline needs further attention. "People have studied sulfur a lot with respect to this problem and have found no strong evidence that it plays an important role. Nitrogen has not been studied as much," explains Johnson, arguing that it deserves greater scrutiny. This debate is more than academic, since advocates of acid rain control have called for legislation that would require more extensive use of scrubbers to remove sulfur compounds from power plant emissions on the assumption that this sulfur is responsible for the damage. The largest sources of nitrogen pollution, in contrast, are automobiles and agricultural sources.

Considerable research is focusing on the roles of sulfur and nitrogen in forests and on the potential impact of an overloading of either material from atmospheric deposition. Some scientists, however, believe the problem lies not with these materials but with ozone, which is very damaging to plants. Ozone occurs naturally in the lower atmosphere in small concentrations and in the upper atmosphere, where it filters ultraviolet radiation from the sun. It is also formed by photochemical reactions involving nitrogen oxides and volatile organic compounds released into the atmosphere during fossil fuel combustion, particularly in automobiles.

It is this anthropogenic ozone that has scientists worried, since only slight increases above natural background levels change the compound's role from that of a natural cleansing agent to a pollutant that could damage plants, materials, and human health. Perhaps the most dramatic example can be found in the San Bernardino Mountains of southern California, where, over the past 30 years, tens of thousands of stately lodgepole, ponderosa, and Jeffrey pines have died. Scientists are largely in agreement that the cause of this dieback is ozone pollution emanating from the Los Angeles basin. The southern Appalachians and much of Germany are often subjected to potentially harmful levels of ozone, and there are widespread symptoms of ozone damage in both regions. Few data have been collected on ozone levels in northern New England forests, and the compound's role in that region remains to be determined. EPRI is currently considering several research proposals to study the effects on trees of ozone in combination with acidic deposition.

Some researchers believe that atmospheric deposition of heavy metals could be contributing to some current forest decline, particularly in Europe, where leaded gasoline is still widely used. Heavy metal toxicity is widely accepted as the cause of dieback in forests close to large ore smelters in Sudbury and Wawa, Ontario. More controversial is the claim that the long-range atmospheric transport and deposition of heavy metals is causing damage to forests far from pollution sources.

No single, simple answer

Much has been learned in the past several years of research, but many questions remain. One of the most important issues yet to be resolved concerns the relative contributions of various pollutants to the damage being documented in forests. Is ozone the principal agent of harm, or do nitrates, sulfates, or heavy metals play a more important role? John Huckabee stresses that it is foolish to look for one causative agent. "Forest decline," he observes, "is probably the result of the interaction of many factors." EPRI Project Manager Lou Pitelka adds that although a combination of elements may be responsible, there still may be critical stresses, stresses that—like the straw that breaks the camel's back—can push a forest from a vulnerable but stable condition into decline.

Some ask if we should be seeking ways to reverse the harm that is now occurring in forests. They point to liming programs in Scandinavian and Adirondack lakes, which neutralize the acidity in lake waters and aim to return the lakes to their earlier state. Nutrient fertilization in weakened German forest plots has produced limited but apparently successful effects. These results raise the hope that similar efforts could help restore damaged forests. Although this may be the case, the great uncertainty about causes of forest decline has prevented surefire mitigation strategies from being developed.

To develop fair and effective solutions, we must recognize the richness and complexity of the problem. There is no single, simple answer. Forests in New England and Germany may be the victims of fundamentally different stresses that call for unique responses. Many hypotheses have been proposed, and the forests are teeming with scientists searching for answers. But nature does not yield her secrets easily, and, whether we act now or later to control what we believe is causing the damage, scientific understanding of the problem will come slowly, as research unravels the agents and mechanisms of forest decline. ■

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This article was written by Michael Shepard. Technical background information was provided by John Huckabee, Robert Goldstein, and Louis Pitelka, Energy Analysis and Environment Division.

Scoring High on Conservation

Three northern utilities are now testing the Princeton scorekeeping method (PRISM), a computer code for evaluating the effectiveness of utility residential conservation programs. The goal is to come up with an easy-to-use, standardized tool that can be applied by all utilities, regardless of size, location, or fuel base.

Utility conservation programs run the gamut from information to audits to retrofit financing. All of them aim at cutting energy use. Yet their success is often measured by the number of participants rather than the amount of energy saved. Do such programs really save energy? And if so, how much?

Tests are now under way with a scorekeeping model—PRISM (Princeton scorekeeping method)—that can help provide the answers. Adapted by Princeton University researchers from their earlier work monitoring energy savings in oil- and gas-heated homes, the present version of the model is ready for application to homes heated but not cooled by electricity.

Three northern utilities are using PRISM on a trial basis to measure conservation savings in heating-dominated climates. They are General Public Utilities in New Jersey, Northeast Utilities in Connecticut, and Puget Sound Power & Light Co. in the state of Washington. All have large-scale conservation programs in place that they want to evaluate. Testing began in January, and initial feedback is expected this fall.

The point, according to EPRI Project Manager Gary Purcell, is to "move PRISM into the real world of utility applications. So far, the method has been developed and tested mainly in university and research settings. We want to see how easy it is for the inexperienced utility user to apply and how useful the results are to utilities. If there are improvements to be made, we want to make them before the method goes into widespread use."

Overseeing this technology transfer for EPRI are Richard Goeltz and Eric Hirst of Oak Ridge National Laboratory (ORNL). The laboratory is itself a PRISM user, having adopted the method in 1983 for a scorekeeping analysis of Bonneville Power Administration's residential weatherization programs. According to Hirst, who is working with both Princeton and the field-test utilities in managing the transfer, "PRISM cleans up the raw data so you can identify program savings."

Applying the method

PRISM uses a simple before-and-after comparison to gauge the effects of, say, a home insulation retrofit. The comparison hinges on an indicator called NAC, for normalized annual consumption.

Margaret F. Fels, a developer of the Princeton method, describes the NAC in-

S C O R E

	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter
Home Team— before conservation retrofit	4632	4787	4691	4917	4613	4778	4670	4862
Home Team— after conservation retrofit	4406	4558	4471	4691	4386	4549	4459	4596

(in kWh)

dex for homes as analogous to the EPA miles-per-gallon rating for cars. NAC measures what a house's energy consumption would be during a year of typical weather. Savings are then estimated by taking the difference between the NAC ratings before and after retrofit.

The NAC rating is derived from three parameters calculated by the model: base-level consumption, heating slope, and reference temperature. Base-level consumption is electricity use that occurs regardless of the weather; consumption for lighting is an example. The reference temperature is the average daily outside temperature that signals activation of the home's heating system. And the heating slope tracks the amount of additional energy required to keep the house warm as the outside temperature falls. It measures the kilowatthours of energy consumed for each degree drop in outside temperature below the reference level.

The fact that the reference temperature in this model is variable distinguishes the Princeton approach from most previous work. In addition, PRISM employs refined statistical methods to check the reliability of each estimate. The program itself can tell the user how much confidence to place in its outputs. "When you estimate a reference temperature," says Fels, "you also know how good that estimate is. No other method does this."

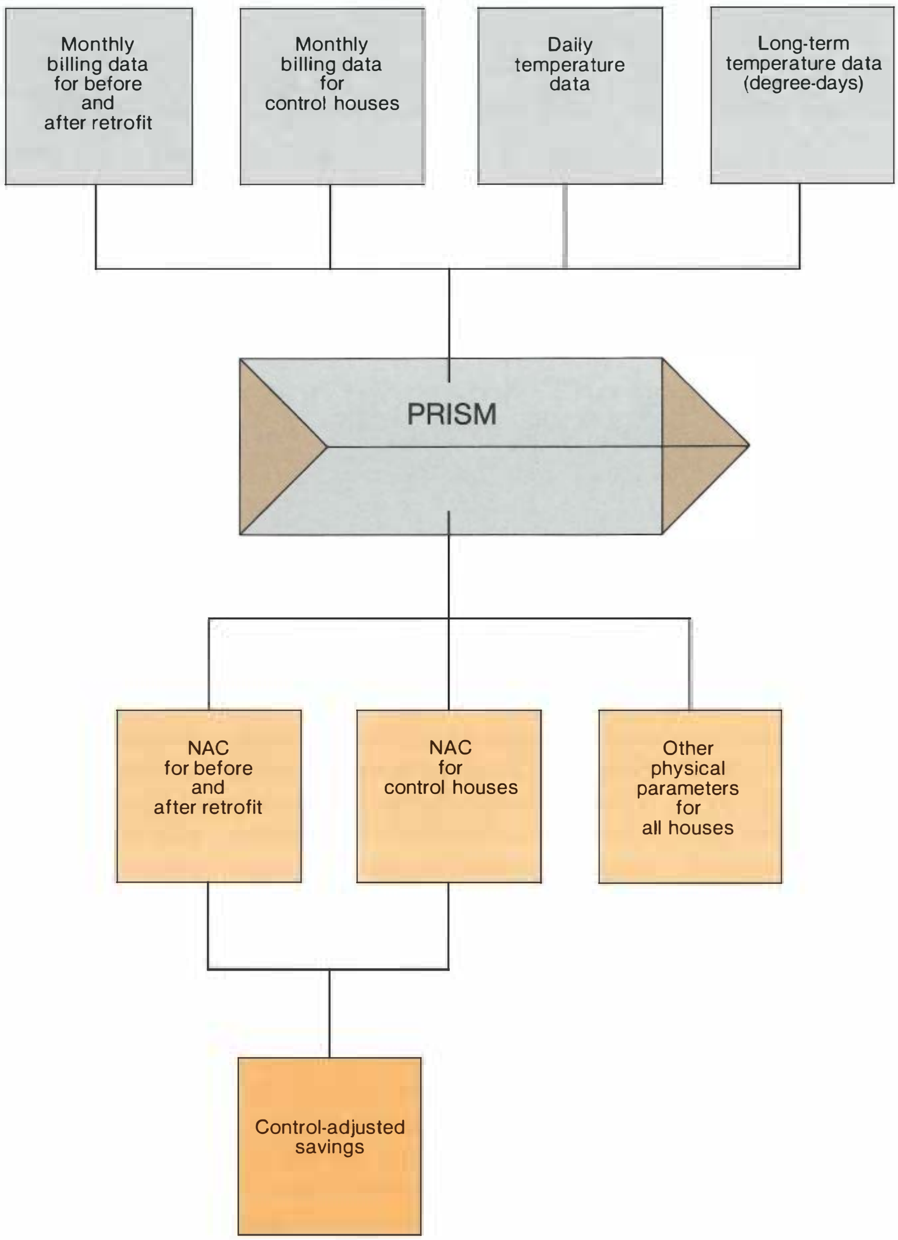
Data requirements for PRISM are straightforward. The utility inputs its own billing data and the average daily temperatures from a nearby weather station. The outputs are the parameter estimates, plus an NAC estimate that is automatically adjusted for variations in the length of the billing periods and for changes in the weather.

To interpret these model outputs, the utility may use survey data that are typically collected as part of a conservation program. It is important to know, for example, whether the same people occupied the house throughout the program period. Especially for data on individual houses, analysis requires a thorough consideration of uncontrolled physical factors that could affect the estimates, as well as attention to standard errors and other statistical indicators. Fels emphasizes "the human element in this process—the need for a careful data analyst who can give a sensitive interpretation to the model results."

At present, any mainframe computer equipped with a FORTRAN 77 compiler can run PRISM. But efforts are under way to scale down the program for sup-

The PRISM Model

To evaluate the effectiveness of a conservation program, PRISM compares energy consumption before and after retrofit, in contrast to most other programs, which measure their success by the number of participants involved. One attractive feature of the PRISM model is the simplicity of the data requirements. The utility uses its billing data and basic temperature information to make normalized annual consumption (NAC) estimates for the study houses and a group of control houses. Savings are figured by comparing these estimates.



plementary use on microcomputers, and Fels is optimistic. Such a move, she points out, "will make PRISM more accessible to small utilities. And that is an important part of the development effort. Our aim is to produce a scorekeeping method that is standardized—one that can be used by all utilities, large or small, for all climates and for all fuel types."

Transferability, then, is also a unique feature of PRISM. Whereas utilities in the past have had to create their own ad hoc scorekeeping methods or at best make major modifications to those produced by others, PRISM is designed to work for any utility without basic alteration. Also, the use of a standardized approach makes it possible for utilities to exchange data and results so that they can benefit from one another's experience in planning and evaluating conservation efforts.

Strengths and limitations

Results from the earlier tests conducted by Princeton University suggest the strengths and limitations of the method. This work (for which a final report is in production) offers a preview of what to expect from PRISM in its current field applications. Because of the difficulties of modeling total heating and cooling consumption for northern households with a weak or erratic cooling demand, the emphasis here and in the field tests is on the final preparation of a heating-only model.

Princeton's sample runs show the NAC index, the cornerstone of the PRISM savings estimates, to be an extremely solid indicator of energy use in electrically heated homes. Standard errors are typically no more than 3–4% of the estimates. These low standard errors suggest that estimated NAC savings of 6% or more may be considered significant. Individual parameter estimates are less robust, but they can still offer valuable clues to the sources of conservation. For example, a house with an improved NAC rating following a weatherization

Utility Conservation Programs

The many conservation programs offered by utilities cover a wide spectrum of homeowner options for cutting back on electricity consumption, including insulation and weatherization, use of energy-efficient appliances, and solar technology. PRISM can help utilities evaluate how effective their programs are and which conservation methods are most cost-effective.

Called a model community for conservation practices, the Hood River area in northern Oregon is part of the nation's largest residential conservation research project. By studying the 3300 homes involved, many partially heated by wood, researchers hope to learn if conservation efforts will offset the region's forecasted increase in energy demand.

program may show no change in the base-level estimate but decreases in the heating parameters. Such findings are encouraging, since they suggest that the savings are due to the retrofit rather than to, say, the purchase of more efficient appliances.

Most straightforward are the findings for homes heated by conventional electric resistance systems. In contrast, houses with heat pumps and houses with supplemental wood burning pose special problems for scorekeeping.

Because heat pumps do not respond in a linear fashion to changes in outdoor temperature, using a linear model to predict their energy use leads to distorted results. Reference temperature estimates, for instance, are typically 5°F (2.8°C) too low. Fortunately such distortions in the parameters are systematic, so they can be corrected during a thorough analysis. Even better, the NAC index seems immune to such problems. It captures total electricity use just as well for houses with heat pumps as for those with resistance heating.

Houses with supplemental wood burning raise thornier issues of interpretation. For example, in Princeton's analysis of data from utility weatherization programs in the Pacific Northwest, wood users as a group showed significantly greater savings than other retrofit customers. Their average NAC rating changed from over 24,000 kWh/yr to 20,000 kWh/yr during the study period, an annual savings of over 4000 kWh. Retrofit customers who did not burn wood saved only 2000 kWh.

The puzzle was that the measured changes in electricity use correlated so poorly with the reported changes in wood use. The increase in supplemental fuel burning reported by the wood users was simply not great enough to account for their doubly large reduction in electricity consumption. Either the wood users' reports were inaccurate, or they included other electricity conservation measures, or both.

The conclusion of this analysis was that the fact of substantial wood use seems to be a better predictor of significant electricity savings than the reported amount of wood use is. An upshot is the possibility that wood users are people with a marked propensity for saving energy in a variety of ways, a characteristic that could make them particularly receptive to utility conservation programs.

Additional work under this same project steers PRISM users away from potential pitfalls. For instance, what should a utility analyst do when meter readings are missing or when only bimonthly data are available? Tests show that 12 monthly readings are optimal, but the research also offers practical guidelines for obtaining reliable estimates in those less-than-optimal situations that scorekeepers frequently have to face. Still other findings help analysts handle the complicating factor of seasonal appliance use when breaking down their heating versus nonheating estimates.

Overall, Princeton's preliminary studies under RP2034-4 support optimism that PRISM will work for all classes of electrically heated houses, even those with heat pumps or wood stoves, as long as the results are interpreted with care. The savings estimates it provides appear far more accurate than the engineering estimates sometimes used in an effort to gauge program viability. Engineering estimates fail to take adequate account of human behavior or of the irregular heat flows that occur in real buildings. PRISM, whose estimates are calibrated to actual kilowatthour consumption and are fortified with built-in reliability checks, is able to move beyond these limitations.

Future PRISM development targets two areas. One involves dealing with problem houses in a data base—houses that do not respond predictably to changes in outdoor temperature. The other involves the incorporation of cooling into the scorekeeping methodology, so that it can be used to monitor savings in houses both heated and cooled by electricity.

Working in stages

PRISM is a versatile tool for managing the large amounts of raw data that typically accrue during a utility conservation program. It can, for a start, provide clues to anomalies in the billing history that have to be weeded out before a full analysis proceeds. Referring to ongoing research at ORNL, Eric Hirst says, "We use the PRISM scorekeeping results to backtrack and identify likely errors in the billing data."

Moving forward, PRISM supplies the standardized first stage of a conservation program evaluation. From complex data it creates simple household NAC ratings that cut across differences in billing cycles and weather. Researchers can then probe why the billing- and weather-adjusted consumption ratings still vary across time or from one household to the next.

"We take the PRISM outputs and use them as inputs to further statistical models," explains Hirst, "to see how normalized electricity consumption is a function of such factors as program participation, house size, changes in energy price, or changes in household income. This second stage of the analysis is to identify what part of the total savings estimated by PRISM is due to the program itself." The final stage in determining the cost-effectiveness of a utility conservation effort is to attach dollar values to these net savings estimates and then measure them against the dollar cost of the program.

Managing both the basic and applied aspects of EPRI research with PRISM, Gary Purcell takes a pragmatic view of the method's value to utilities. "We want to know how much good it really does to apply a certain level of insulation," he concludes, "and whether the savings justify the costs. PRISM represents a solid first step toward getting us accurate answers."

This article was written by Mary Wayne, science writer. Technical background information was provided by Gary Purcell, Energy Management and Utilization Division.

Raphael Thelwell: Pursuing the Social Economics of R&D

This university professor and former industrial engineer pioneered the federal government's five-year budget projections and spent three years as an NAACP economist. Now as an EPRI adviser, he looks at the economic implications of utility research.

Raphael Thelwell is tall and spare; he leans into his long-legged stride, and his head seems to lead the way toward his fifth-floor office in Howard University's newest academic building, the School of Business and Public Administration.

Height gives Thelwell one special view of the world; he stands 6 feet 6 inches. His nine years on the faculty of a leading black university afford another outlook. And his office setting, with its window toward the U. S. Capitol and the monuments on the Mall in Washington, D.C., symbolizes still another: he spent nearly 14 years with the Office of Management and Budget and the House Committee on the Budget. It is no figure of speech that Ray Thelwell's head has led him, thoughtfully, to each of these viewpoints of U.S. society.

For most of his time at Howard, Thelwell has taught economics and statistics, conducted research on social indicators and national economic policy, and consulted on management problems with the Department of Defense. During a three-year leave begun in 1980, however, he applied all his management, budgetary, and economic expertise in working as director of economic analysis for the National Association for the Advancement of Colored People. And in 1983 he accepted an appointment to a four-year term on EPRI's Advisory Council.

The Advisory Council is EPRI's window on the world beyond electric power technology and the electric utility industry. Its 25 members are drawn from academia, commerce, government, and industry; from a wide range of professional, business, and trade skills; and from numerous areas of societal, environmental, and economic interest. The combinations of individual backgrounds are endless, and although Thelwell closely followed the NAACP's Margaret Bush Wilson to an EPRI advisory post, he

"We're settling for an average of 7–7.5% unemployment today. That controls inflation fairly well, but it produces depression-level conditions in the minority community, where unemployment is around 15%."

is not inclined to see himself as a representative of a racial or ethnic group. "I try not to think in a racial way," he says of his long work with national economic policy. "That's not really the point of it. I think of it more as equal opportunity. And the constituency isn't minorities, but low-income people."

Moreover, if the Advisory Council is a window on the world, then Thelwell is also looking in, as much an observer of EPRI as an adviser, studying the industry and its moves, interested less in the technologies of electricity than in their implications for the economy.

Building a profession

Large, thin-rimmed glasses accentuate Thelwell's eyes and his alert, eager expression. His forehead rises to a long-since receded hairline; his frequent smile stretches a wide mustache. He speaks softly and ever more easily as discussion moves away from himself and toward the topics to which he has devoted most of his 34-year professional career.

He only briefly recounts his return home after World War II. "I lived in New York, I was on the G.I. Bill, and I went to Columbia University—for me it was a neighborhood school—where I majored in industrial engineering." That field was relatively new, he recalls, and it went well beyond its origin in the practices of so-called production efficiency experts. Still, the focus was on industrial rather than business management, on the factory rather than the front office. "So it was a regular engineering curriculum plus your electives in this area," in Thelwell's words, and he earned both bachelor's and master's degrees, the latter at Stevens Institute of Technology during his early years as an engineer at the Army's Picatinny Arsenal in New Jersey.

Later with the Army Management Engineering Training Agency at Rock Island Arsenal in Illinois, Thelwell was on the ground floor when the Army developed and introduced the project management concept for its research and development units. Activities of the Ordnance, Transportation, Signal, and Quartermaster corps were combined as the new Army Materiel Command, for which Thelwell supervised design of an R&D management system. Warming to the memory, he adds, "We were written up as the primary source of information on project management at the time, which was a sort of feather in our cap because the Air Force was our competitor; it poured millions into the activity, but we managed to scoop them for a couple of years."

Thelwell was teaching by this time—applied mathematics, statistics, and industrial engineering for DOD at Rock Island Arsenal, as well as operations research at the University of Iowa—so the transition into the Army agency's consulting work for DOD and other federal departments was an easy one. The Bureau of the Budget (now the Office of Management and Budget) was one such client, and in 1963 it offered Thelwell a position in Washington. Again, memory livens his account. "The kids were about ready to go to school. It was time for career reassessment. And I guess I was one of the few people invited to the Bureau with a promotion. They were in the executive office of the President, right at the center of government; so I came."

Efficient function was and is an objective of Thelwell's professional study and practice. "I had been interested in efficient management. Now that I was in Washington, it became efficient government. At first I was the staff member for industrial engineering," he continues, "going around to other agencies and worrying about how they handled that function. Later we formed management teams that spent six months to a year in an agency, studying everything."

The focus of these audits became a matter more of managerial effectiveness and less of measurable efficiency in the use of money. As Thelwell tells it, "We changed from being a green-eyeshade group to one that looked at the substantive questions about what an agency did, how well it was done, and why." A transition was thus under way that would shortly find its way to the General Accounting Office and thereby throughout the federal government. Oddly, however, management research was abruptly deemphasized at the Budget Bureau in the late 1960s, and Thelwell found himself pioneering again, this time developing a system for making five-year federal budget projections.

Taking a stand

In the past, neither the Bureau of the Budget nor any other federal office had submitted a budget that went beyond the succeeding year. Thelwell completed and introduced the new procedure in 1968, and the so-called future outlook section of the federal budget was thereafter prepared under his guidance until 1974. As with management audits a few years earlier, this new practice quickly spread throughout the federal establishment.

Until the 1970s, for example, all 37 committees of Congress were handling portions of the federal budget independently. It was difficult for Congress to gain a holistic view of the budget, and both houses became very concerned, "especially," comments Thelwell, "when Nixon began to impound money."

Thelwell's comment refers to President Nixon's hotly contested practice of impounding congressional appropriations that seemed to inhibit the objectives of his administration. For many people, Nixon's notoriety is their memory of the action, but Thelwell sharply recalls its economic and political significance, and this memory causes him to twinkle. "You see, Washington *is* a different place. We concentrate on government affairs almost exclusively!"

Because of the dissatisfaction in Congress over its control of the budget, the Congressional Budget Office was created, as well as a pair of new committees, one in the Senate and one in the House. The House Committee on the Budget would be Thelwell's final point of federal service in 1974 and 1975 when, as its fifth staff member hired, he served as a senior analyst responsible for House projections of the budget, studies of controllability, and research into economic stimuli. Reflecting on that work, he credits the two congressional committees for much of today's awareness of the growing federal deficit. "That's why we have this real concern about its consequences two, three, four, and five years from now."

The end of the 1960s saw a major transition taking shape in Thelwell's life. He was teaching and doing graduate work at George Washington University toward a 1973 doctorate in business administration, which would be important in his eventual move to Howard University. But more immediate and far more obvious in its influence was an event that arose out of the 1968 presidential election. "Nixon was coming in," Thelwell recalls, his thoughts falling from a calendar in his memory. "Our new director at the Bureau of the Budget was George Shultz—the man who is now Secretary of State. And at that time there were only 5 black professionals on a staff of more than 500."

Thelwell reaches for the right expression of his own reaction. "Until then I was simply a professional worker. I hadn't identified with minority issues—I was aware of them, of course—but that occasion was an issue I had to take a stand on. The five of us sent Shultz a telegram, pointing out the problem we saw, and when he got to the White House, he invited us over to talk. As a result, within a year or two there were more than 60 people from minorities in professional capacities on our staff."

Activism as such has not been a thread in Thelwell's life since then, but the heightened awareness of minorities remains. It encouraged his decision to join the Howard faculty in 1976, after two years with the House Budget Committee, and it guides much of his academic research in economics today. It most certainly drew him to the NAACP in 1980.

"I've never felt uncomfortable about increases in productivity [having an effect on labor]. The only increases in the standard of living come from producing more with the same inputs."

Defining economic minorities

The NAACP assignment was especially challenging because, once again, it was an opportunity for Thelwell to break professional ground. He had been an instructor, teacher, and consultant at many times over the years, and much of his early association with Howard was an extension of that enjoyable work. But the NAACP's economic analysis unit was new, and his charge was to develop an economic capability for focusing on minority issues and recommending courses of action.

This task was not to be one of simply putting a numerical basis underneath existing NAACP policy. In Thelwell's words, "My full-time occupation was to interpret federal policies in terms of their effect on minorities. You can look at just about anything," he goes on, "and there's one type of analysis you'll make if you don't think of minorities. You just include them as a fraction of the population and you'll come to some conclusion. But there's a different analysis if you decide to examine how a particular policy will affect them."

In this light, one of Thelwell's first big NAACP tasks was to analyze the budget of the new Reagan administration. "Some of the recommendations we made then are just now coming through; the new tax proposal, for example, that individuals below the poverty line shouldn't be taxed." Thelwell's report five years ago foresaw that Reagan's program would produce more unemployment, much of it in low-income groups, and that taxation in those same communities would further reduce their economic resiliency.

Thelwell's argument by itself does not particularize racial or ethnic minority problems or needs, although some are intuitively evident and more can be documented by analysis. His foremost con-

"Most of EPRI's work accrues to society in general rather than to the utilities that finance it. That's partly why utilities tend to underinvest in R&D."

cern is the social cost of unemployment, the nation's consciousness of it, and our policy response to it. He reaffirms an observation he made at EPRI's Advisory Council seminar two years ago, when labor utilization figured heavily in a discussion of productivity. "If the United States accepts the premise that full employment means 7–8% unemployment," he warns, "then the cost of supporting the unemployed must be borne by society no matter how we slice it. And that cost is a tremendous drag on the economy."

Historically, full employment in the United States has meant about 4% unemployment. The rate was above 7% for two years before Reagan took office, and it is only now back down to that level. "If you want to be hard-nosed about it," says Thelwell, "our society's threshold of pain is somewhere up around 10.5%—that was the unemployment rate when we took action, when the Federal Reserve Board loosened the money supply to fuel the recovery. Still, we're settling for an average of 7–7.5% unemployment today. That controls inflation pretty well, but it produces depression-level conditions in the minority community, where unemployment is around 15%."

Again Thelwell becomes animated over the ramifications of his topic. "Studying what happens 'on the average' is entirely different from what you need to do in addressing particular problems. A democracy works on the basis of averages, but an average solution doesn't always work for minorities." Should a democracy function differently? Thelwell shakes his head and even responds twice for emphasis. "I don't *think* it should. I don't think it *should*. But you know, you develop a philosophy on these things as you go along, and what I'm coming to find is that national economic policies can create economic minorities."

Carrying a given policy into legislation may produce widespread benefit as intended, he explains, but it frequently exacts its costs from only a few demographic or economic segments of society. Generally, he says, "the bottom of the labor market is the cushion for the business cycle, and it pays the most." But sometimes another minority suffers.

"Take the farmers. Much of their problem is due to a tight money policy, which produces high interest rates and an unfavorable exchange rate. There may be benefits for everybody else, but should farmers have their fortunes and futures wiped out because of that? We need a social mechanism to compensate the people who—through no fault of their own— are paying the price. If a policy is a good one, that compensation ought to be one of its benefits."

Documenting R&D benefits

When Thelwell came to EPRI's Advisory Council, he brought along his sensitivity to the costs of economic policies and the groups who pay them. He is most interested in the implications of electric power research for labor productivity and for the unit price of electric energy. "Even if electricity prices don't come down," Thelwell declares, "they need to be kept from rising any more than absolutely necessary, because electricity is such a large part of a low-income family's budget. Not only that, but in most instances—where utilities have declining block rates—those families pay at the highest rate."

But what about electricity-intensive processes that build productivity, seemingly at the expense of labor? Thelwell's industrial engineering background has not left him. "I've never felt uncomfortable about increases in productivity," he states. "Innovations and new products have always come along as fast as old ones are phased out, and they provide better-paying jobs. Increases in the standard of living come only from producing more with the same inputs."

In an aside, he also remarks, "You know, it's just not right to use people inefficiently, or to cut their output, just to keep them employed. In view of all the things that still need to be done in our society, we ought to be able to employ everyone at maximum capability and maximum efficiency."

During Thelwell's three years of EPRI advisory service, two other matters have particularly caught his attention. One is the complex of utility viewpoints, capabilities, interests, opinions, and even tensions stimulated by the question of raising the industry's level of R&D investment. The other is the character of EPRI reportage, especially some ideas for organizing research results more logically and making them more prescriptive.

Thelwell's thinking on R&D funding underscores his stated conviction that nationwide productivity gains are essential. He expresses concern that EPRI is not sponsoring and managing the amount of research that is socially needed. And he sees a tension, a paradox, among the utility industry's leaders.

On the one hand, as technology managers they recognize the need for R&D. On the other hand, as businessmen their dollar votes primarily bolster their short-range position.

Thelwell thinks aloud on the matter. "Most of the benefit of EPRI's work accrues to society in general rather than to the utilities that finance it. That's partly why utilities tend to underinvest in R&D—it doesn't appear rewarding. Now there are market signals that EPRI needs to do more research in customer end uses of electricity. Much of this has a conservation or load-management angle; so in the short run, anyhow, it's in the direction of being even less rewarding to utility investors."

The search for solutions to EPRI's funding problem intrigues Thelwell, but he is frank to say that EPRI needs better documentation of need than the kind of recommendation the Advisory Council offers. "We may say, 'It ought to be done' or 'You should raise the budget by 10%,' but," he concludes flatly, "there isn't any type of management, except where one guy at the very top controls the whole thing, that would accept that kind of analysis.

"EPRI already knows," he goes on, "what is being lost as a result of not doing more research, and how much is being invested by electric utilities relative to other industries. What's needed is to pull that together and clearly show the public what's the benefit and what's the cost."

Persuading others

Although Thelwell clearly comes down on the side of well-documented economic justification, he also recognizes the place of persuasion and of a united front among people in pivotal roles. Seven members of the Advisory Council are utility commissioners, members of public regulatory bodies in various states; and those individuals uniformly endorse a more aggressive R&D program by electric utilities. Thelwell looks beyond their gesture.

"A few commissioners have gone on record in their own areas," he says, "but there's been no overall position that more extensive R&D is in the best interest of ratepayers." Thelwell has in mind the National Association of Regulatory Utility Commissioners (NARUC). "As a body, they could clearly enunciate a position, at least the outer parameters of what they see as desirable. This would be a signal to utilities, which would then make their own decisions, allocating funds to EPRI—or elsewhere—to achieve their objectives."

Thelwell's other main advisory interest concerns organizing and delivering EPRI's research output in a more prescriptive fashion. As he sees it, this matter is mostly one of communications. He envisions periodic catalogs, or perhaps data bases, organized after the hierarchy of a power station or unit, its subsystems, assemblies, components, and procedures for operation. "A utility could go through its design criteria to come up with the right configuration," Thelwell says. "Then EPRI's catalog or data base would present the optimal solution, based on its research up to that time."

Thelwell likens the idea to a Sears catalog, admitting, "The idea may be a simple-minded one at this point. Reality is probably somewhere in between. But it appealed to me, and it's one of the things that I wrote to Floyd Culler about."

His letter to EPRI's president addressed only one other matter, the suggestion that NARUC officially endorse a higher level of utility R&D investment. Thelwell chose to write for various reasons, not the least being the longstanding wisdom that "the higher you go, the more receptive the person is to ideas." In a related comment he adds,

"What I'm coming to find is that national economic policies can create economic minorities. . . . The bottom of the labor market is the cushion for the business cycle, and it pays the most."

"It's always easier to talk to the president than to anyone else. And in any event, Floyd is an easy person to talk to."

The remark is a reminder that Thelwell is mostly an observer of EPRI, choosing very carefully the instances where he offers commentary, including this one. "I often feel that I don't know enough about the relationships in the whole utility industry. From my experience, so much of a real solution depends on understanding the subtleties, it's really not worth popping off with simplistic solutions. Thinking of myself as a consultant on management problems, I really wouldn't advise EPRI on the basis of the information I have."

Thelwell acknowledges a sharp difference between himself and some other Advisory Council members in this respect, but he gives no impression of justifying himself. He is simply responding to his own temperament. "I don't have any problem with their approach," he concludes almost wistfully. "In fact, sometimes I'd like to sound off more, but it's just not my style." ■

This article was written by Ralph Whitaker and is based on an interview with Raphael Thelwell.

Direct Load Management Implementation Plan Cuts Costs for HL&P

Direct load management programs can help utilities cope with the troublesome problems of matching customer demand to system capacity, but their implementation can also burden utilities with significant startup labor costs. Consequently, before initiating its new direct load management program, Houston Lighting & Power Co. (HL&P) needed a way to carefully design its implementation plan. HL&P turned to the results of an EPRI project that had studied several utilities familiar with direct load management and had distilled their experience into a number of simple procedures. Using the EPRI format, HL&P completed two activity charts constructed to identify interrelationships among the activities involved in defining the critical issues in HL&P's load control situation. Reliance on the charts substantially reduced the planning and lead time for the program, and HL&P estimates a one-time saving of $10,000. ■ *EPRI Contact: Clark Gellings (415) 855-2610*

Outage Guidelines Provide Yardstick for Transmission Reliability

Like other regional utility organizations, the Mid-Continent Area Power Pool (MAPP) is working to develop yardsticks for measuring the reliability of its bulk power transmission system. MAPP's Transmission Reliability Task Force needed a method of categorizing transmission outages that grouped the outages by type, so that an average or standard could be determined. Guidelines developed under EPRI contract by General Electric Co. for reporting and recording specific outages filled the need. The guidelines offer a set of consistent definitions, formats, and procedures for reporting problems with transmission facilities. Before MAPP adopted these guidelines, each utility had to keep tabs on its own outages and lacked a wider basis for comparing outage rates. The system is already proving its worth: in one case a MAPP member compared outage rates with the average and was able to pinpoint an ongoing problem in a 345-kV line. With repairs, the utility will save an estimated $113,000 annually. ■ *EPRI Contact: Neal Balu (415) 855-2834*

DETGEN Handles Fuel, Marketing, and Financing Strategies

Utility analysts continually have to account for a growing number of uncertainties—such as demand growth, the availability and performance of new technologies, and fuel supply—as they engage in planning activities. Increasingly, they are recognizing the value of decision analysis and decision trees in representing these uncertainties. Now a code is available from EPRI's Electric Power Software Center that can help analysts make a generalized evaluation of such decision trees. Called DETGEN (for decision tree generator), it can be used to formulate and solve virtually any type of problem that can be represented by a decision tree—including technology and fuel supply choices, financing options, and marketing strategies. DETGEN is simple to use and has saving and retrieval features that speed repetitive analyses; its convenient and flexible format accepts a variety of decision tree structures. It is fully validated and runs with little or no modification on systems supporting FORTRAN. Because its numerical algorithms require few iterations and little storage, DETGEN is inexpensive to run. The code is available in both mainframe and microcomputer versions. ■ *EPRI Contact: Lewis Rubin (415) 855-2743*

Montana-Dakota Planners Use EGEAS to Select Power Options

To meet an increasing demand for electricity, generation planners at Montana-Dakota Utilities (MDU) had to study a variety of power options in terms of growing financial and regulatory constraints. Lacking an adequate in-house capacity expansion model and the resources to develop new software, MDU searched for a program that could meet its needs. What it found was EGEAS (electric generation expansion analysis system), a computer program developed for EPRI by the Massachusetts Institute of Technology's Energy Laboratory and by Stone & Webster Engineering Corp. EGEAS provides a unified data base and improved algorithms to enable a user to choose from among several generation expansion alternatives. By integrating three separate analyses, it handles complex generation expansions with flexibility and a minimum of personnel and computer resources. The model has helped MDU successfully identify its most attractive power supply options. Although an EGEAS conversion from IBM to Prime cost MDU $4400, it realized a net savings of $115,600 over the cost of an alternative program. The EGEAS program is currently distributed to more than 65 member utilities. ■ *EPRI Contact: Neal Balu (415) 855-2834*

ATHOS Predicts Steam Generator Performance, Saves RG&E Money

Nuclear power stations have often had to suspend operations for reinspection within 30 to 60 days following significant steam generator tube repairs. After comprehensive repair work on one of its steam generators, Rochester Gas & Electric Co. (RG&E) wanted assurance that it could safely operate its Ginna nuclear plant over the summer peak without shutting down for reinspection. To assess poststartup thermal-hydraulic phenomena, RG&E relied on ATHOS, a three-dimensional, two-phase flow distribution code that describes secondary-side velocities, pressures, and temperatures and primary-side tube wall temperatures. Modified to reflect the revised geometry of the Ginna steam generator, ATHOS showed good agreement with analyses by the steam generator's original manufacturer. On the basis of the ATHOS calculations, RG&E affirmed its decision to delay the Ginna reinspection outage for 120 days—well past the summer peak. The generator performed as predicted, and RG&E saved an estimated $110,000 over alternative calculated costs. ■ *EPRI Contact: Govinda Srikantiah (415) 855-2109*

"Attractiveness Cube" Eases Marketing Decisions at Consumers Power

Normally the most difficult part of developing a successful marketing plan is integrating a large array of technical, financial, and institutional factors into a cohesive strategy. If, like Consumers Power Co., you have to reach a combined (gas and electric) market, the problem of developing an integrated marketing approach is even more complex. Seeking a better way to set marketing priorities, Consumers volunteered to take part in a study being carried out by Booz, Allen & Hamilton, Inc., under EPRI contract. The result: a decision-making framework that Consumers estimates will save nearly $14 million over four years. Called an "attractiveness cube," the new tool displays key trade-offs on orthogonal axes within a three-dimensional form. Using the cube, Consumers can quickly integrate important functional information, clarify trade-offs, and rapidly decide how best to meet overall objectives. The cube summarizes complex and diverse details and makes it possible, according to Consumers' Stephen Etsler, "for everybody to see where the real benefits are, and why." ■ *EPRI Contact: Dominic Geraghty (415) 855-2601*

Snohomish PUD Solves Inductive Interference Problem

After Snohomish County Public Utility District No. 1, a Washington State utility, upgraded a 13-mile section of line running next to Burlington Northern Railroad's tracks, the railroad experienced inductive interference on its circuits. The utility's options were not entirely satisfactory: rerouting the line was out of the question; shielding the cables—the traditional remedy—would cost over $1 million; and converting Burlington's communications and signal system to centralized traffic control and microwave would cost $700,000. Snohomish turned to an EPRI-sponsored study, conducted by IIT Research Institute, that was aimed at developing methods and criteria for use by both railroad and utility designers. Employing design methods developed in the study, a consultant worked with Snohomish and Burlington to devise a mutually satisfactory and cost-effective solution to the railroad's inductive interference problem. Total cost to Snohomish: $100,000, including capital expenditures, consultant's time, and in-house expenses. ■ *EPRI Contact: John Dunlap (415) 855-2305*

Automated Scanner Inspects BWR Pipe Welds

EPRI has recently awarded a license to Amdata Systems, Inc., of San Jose, California, to manufacture a new automated pipe scanner that permits remotely controlled ultrasonic inspection of welds in the piping systems of BWRs. Called AMAPS (for adaptable, track-mounted, automated pipe scanner), the high-performance device consists of a flexible guide track, a scanning mechanism, and a low-profile, booted search unit. Because its track can be adapted to a broad range of pipe diameters, surface textures, and component geometries, the scanner can achieve accurate and repeatable positioning during data acquisition. The AMAPS design enables fast (less than five minutes) installation and removal—and hence the reduction of radiation exposure times for inspection personnel. Developed under EPRI-sponsored research, the scanner is available in three models that differ only in weight and their x- and y-axis speeds. Each is mounted on a ⅛-in aluminum-plate frame that provides a rugged, compact package designed for both field and laboratory use. ■ *Contact: Amdata Systems, Inc. (408) 946-6064; EPRI Contact: Soung-Nan Liu (415) 855-2480*

DOE Explores Advanced Energy Projects

Within DOE's Office of Basic Energy Sciences, the Division of Advanced Energy Projects supports exploratory research that tests the scientific feasibility and practicality of novel energy concepts.

The Department of Energy (DOE) is supporting a broad spectrum of energy-related research. At one end of the spectrum are well-established programs that supply funding for basic research—research that pushes the frontiers of knowledge in such areas as biology, chemistry, physics, and material sciences. At the other end are major programs that promote technology development by funding projects to verify the practical application of discoveries and innovations in areas like solar power, nuclear energy, and energy conservation.

A special DOE division, the Division of Advanced Energy Projects, exists for those projects that fall somewhere in between. These are the projects that do not qualify as basic research because the knowledge they embody is already established and proved; nor do they qualify for technology development funding because they have not yet reached the point at which their practical application can be shown. Explains the division's director, Ryszard Gajewski, "These are the projects about which everyone says, 'It sounds like a great idea—there must be someone out there who can support it.' " Thus, in its way, the division prevents many good ideas and potential innovations from slipping through the cracks in the government's R&D funding structure.

Gajewski became the division's first director in 1977. He came to the United States in 1969 from Poland, where he had been a professor of physics and had directed research in plasma theory at the Institute for Nuclear Research. Since coming to this country, Gajewski has taught and conducted research at the Massachusetts Institute of Technology and at Brandeis University. He has also served as director of research for American Science and Engineering, a Cambridge, Massachusetts–based R&D firm.

Having been "on the other side of the fence," Gajewski appreciates the frustration of research scientists who are "nickeled and dimed to death" with inadequate funding and then criticized for achieving only modest results. With an annual budget of approximately $10 million, the division supports 35 to 40 projects with funding levels ranging from $100,000 to $400,000 a year. By limiting the number of projects his division funds, Gajewski can ensure "funding levels commensurate with possible success."

He describes the research grants as seed money, noting that "a grant from this office represents an opportunity to try out an idea, to gain some visibility, to perform the level of experimental research that the ideas and concepts deserve. For many researchers," he adds, "the division offers a unique opportunity because the projects we fund have often been around the funding circuit with no success."

As an example, he cites a proposal from researchers at the Ford Motor Co. to develop a sodium heat engine for direct conversion of heat to electricity. The proposal was submitted to the Energy Research and Development Administration's conservation division and subsequently to the division of solar energy; both deemed the project too speculative for funding. In 1978 the Division of Advanced Energy Projects took the project on, and the laboratory-scale model of the engine was so successful that the research is now being funded by DOE's Office of Conservation.

Finding additional funding beyond the division is a prerequisite for ongoing research because the division supports projects for only a maximum of three years. Gajewski believes that this imposed time limit is an important factor in the division's success. "Our experience has shown that three years is a sufficient period of time in which to demonstrate the viability of a concept. After that point, the success or failure of a project generally is determined by whether or not it is taken up and supported by another entity. In addition, the three-year limit gives us a great deal of flexibility. Every year a third of our projects are retired, freeing up money to take on another 12 to 14 new projects."

Current projects cover a broad spectrum of technology: radically different approaches to fusion, storage batteries with polymer electrodes, new sources of electromagnetic radiation, new heat engines, and novel approaches to coal demineralization.

Proposals come into Gajewski's office from all walks of science, from universities, national laboratories, small research businesses, and industry. An immediate, specific application of a concept is not an absolute prerequisite for consideration; rather, Gajewski and the various reviewers who scrutinize each proposal award competitive grants entirely on the quality of the proposal and the concept itself. As Gajewski explains, "We are always in the responsive mode." He emphasizes, however, that this is not an inventor's program: the level of sophistication exhibited by these projects is generally associated with research institutions rather than private individuals.

Laser and Fusion Advances

One area in which the division has supported a number of recent projects involves novel sources of electromagnetic radiation. These include X-ray and gamma-ray lasers—and a relatively new venture into free-electron lasers. Free-electron lasers are produced by accelerating a beam of electrons almost to the speed of light and then using a magnetic field to cause the beam to "wiggle." It is the wiggle effect that produces radiation. According to Gajewski, the free-electron laser was proposed several years ago, and recent research has implemented a number of innovations to the original concept. The result might lead to radiation with very desirable properties, such as enormous power and very short wavelengths.

The new lasers have potential significance for a number of different fields. In medicine, they could be used to produce extremely narrow "pencils" of X-rays for diagnostic use. In the computer field, the lasers could be put to work in microlithography because microchip etching requires radiation of extremely short wavelength. For industry in general and for the electric utility industry in particular, lasers could have very practical applications in materials research.

Gajewski emphasizes that although these are laser applications that are now under consideration, there could be any number of applications that have not yet been thought of. He cites the example of the optical laser: "Who could have imagined the variety of applications that have evolved from the discovery of optical lasers some years ago?"

Another area that has generated a great deal of interest in the last few years is a radically different approach to fusion, called muon-catalyzed fusion. A muon is some 200 times heavier than an electron and moves in the atom within a much smaller radius. Substituting a muon for an electron in a molecule of deuterium-tritium gas creates a molecular structure so small that the two nuclei fuse spontaneously. Gajewski describes the process as "tricking Mother Nature." The beauty of muon-catalyzed fusion is that it can be achieved at essentially room temperature, without the millions of degrees of heat traditionally associated with the fusion process.

The principle of muon-catalyzed fusion was first introduced in the late 1940s by such eminent physicists as Andrei Sakharov and Luis Alvarez. The idea was dropped because it was largely assumed that the muon would be lost after the initial catalytic reaction. However, researchers funded by the division have recorded as many as 160 reactions from a single muon—a very recent development that has generated a great deal of interest in the scientific community.

Gajewski emphasizes that it is still much too early to tell if the process has the ingredients of practicality. "We still don't know how many reactions per muon would be necessary before the process would be economically feasible—that is, before the energy produced would be greater than the energy required to produce the muon. If it works, however, it would mean a totally new

Gajewski

approach to fusion and a potential means of generating electric power."

High-Risk Successes

Gajewski does not underplay the "ifs" associated with the projects his office funds. From its inception, the Division of Advanced Energy Projects was designated as a high-risk, high-payoff operation. Given this definition, Gajewski fully expects that most of the projects will fail to be picked up and supported after the three-year period. "That's the definition of high risk—that most will fail. Even if there were a 50-50 chance of success, that still wouldn't be high risk," Gajewski explains. Approximately 25% of these projects do go on to receive funding from other sources. Gajewski judges this to be a measure of relative success, given the exploratory nature of the research in the division. More important, there have been payoffs, often in areas where they were not expected.

One example involves holography, a relatively new optical technology. National Technical Systems, a California research firm, received a grant to develop holographic concentrators for solar power. Researchers developed a pattern of imprints on flat sheets that act as mirrors or lenses for solar collection, replacing the bulky collection systems currently being used. During the course of their work, the team discovered that imposing particular patterns on window glass could exclude portions of the solar spectrum. The research in this area has been picked up and funded by DOE's Office of Energy Conservation.

Looking to the future, Gajewski says that he is happy with the budget under which he operates. If the program got too big and began evolving into demonstration projects, its purpose would be defeated. "Too much money only buys you trouble," Gajewski explains. "Right now we are not subject to many external pressures, so there's a lot to be said for staying reasonably small. Anyway, there aren't that many great ideas out there; we haven't had to turn down any truly remarkable projects." ■

This article was written by freelance writer Mark Reynolds.

Seismic Hazard Project Ends First Phase

Coordinating cross-disciplinary research on seismic issues, EPRI's Seismic Center works to develop advanced technology and enhanced design criteria for nuclear power facilities. Now, phase one of a major program has produced significant early results.

EPRI's Seismic Center has announced the successful completion of the initial phase of a major three-year research program to develop methods for calculating the probability of ground shaking at nuclear power plant sites east of the Rocky Mountains. Carl Stepp, manager of the seismicity work carried out at the center, states that "early results have produced reports on a geophysical and seismological data base, a new methodology, and calculations for nine test sites." Funding for the seismic hazard research is provided jointly by EPRI and 42 utilities that compose the Seismic Owners Group. The group has already approved a second phase of research: preparation of a topical report on seismic hazard methodology that will be submitted to the Nuclear Regulatory Commission (NRC) early next year.

Other Seismic Center experiments and analyses have recently contributed to a relaxation of requirements for ASME Boiler and Pressure Vessel Code analysis by demonstrating the inherent strength and energy dissipation mechanisms in plant piping systems. As a result of these and other studies, utilities should be able to reduce their reliance on hydraulic and mechanical snubbers (shock-absorber-like restraining devices) for plant piping systems, thus decreasing maintenance costs and improving system reliability. These projects will also help utilities avoid millions of dollars of unnecessary retrofits.

The Seismic Center was established in 1983 when it became clear that nuclear utilities faced a growing and complex array of seismic issues, issues that increasingly resulted in scheduling and cost impacts on plant design, licensing, construction, and operation. Member utilities owning nuclear plants saw a need for a coordinated effort to resolve these issues in a timely, cost-effective manner.

In response to their concerns, EPRI's president, Floyd Culler, directed the formation of a center within EPRI's Nuclear Power Division to help utilities deal with seismic issues and ultimately improve the licensing and regulatory climate. Research into seismic issues often encompasses a number of disciplines, such as geotechnical, structural, and mechanical engineering. Thus the center, which is an organizational rather than a physical entity, provides a unifying focus for all these areas and the basis for fully scoped, cost-effective ways of resolving seismic licensing issues.

"The responsibility of the Seismic Center," explains John Taylor, vice president and director of the Nuclear Power Division, "has been to coordinate all this seismically related work to ensure that the full breadth of EPRI's professional talent is brought to bear on seismic issues."

To discharge this responsibility, the center oversees a broad range of earthquake research. For example, it has sponsored several geotechnical projects to improve predictions of building motion during earthquakes, including three series of strong motion soil-structure interaction tests, two in New Mexico and one in New York. Called SIMQUAKE 1, 2, and 3, the tests used scale models and buried explosives to simulate the effects of an earthquake on the dynamics between a power plant building and the underlying soil. Resulting data were used to validate EPRI's soil-structure interaction code, STEALTH–SEISMIC.

As an extension to these small-model simulations, the Seismic Center and the Taiwan Power Co. are now completing the construction of ¼- and 1/12-scale PWR containment buildings in Lotung, Taiwan. To monitor this seismically active location, another project participant, the National Science Foundation, has deployed an extensive network of 37 seismometers over a 13-km^2 area. Both the containment building and the internal plant components will be fitted with instrumentation, as will the soil underlying the structure. Yet another participant in the experiment, NRC, is to conduct low-amplitude forced-vibration tests on the scaled containment models to determine soil and structure properties.

In conjunction with the Seismic Qualification Utility Group (SQUG), the Seismic Center also sponsors ongoing equipment and piping seismic qualification research. These efforts rely on historical data (actual records showing the seismic response of equipment in nonnuclear facilities) and equipment seismic test data to evaluate the generic ruggedness of identical or similar equipment in nuclear plants. The work done by EPRI and SQUG shows that enough empirical data exist from these environments to draw parallels to the adequacy of equipment in nuclear facilities, thus permitting utilities to avoid costly requalification programs.

As all these seismic projects suggest, the long-term goal of the center is to generate technically sound design bases for nuclear facilities so that utilities can resolve the seismic licensing and regulatory issues they confront. For example, once NRC receives the generic seismic hazard report due early next year, EPRI hopes that the commission will use it to prepare a safety evaluation report (SER). An SER that delineates procedures would provide utilities with an acceptable methodology for assessing the seismic hazard at sites within the eastern United States.

Such technically supported bases for determining seismic design, EPRI believes, will allow plant owners to use rational design criteria in the near term, which in turn will minimize the cost of addressing seismic licensing issues and increase plant safety and reliability. For the longer term, Ian Wall, director of the center, expresses confidence that "a strong technical basis will ultimately stabilize this aspect of the nuclear plant licensing process and shorten plant design and construction periods." ■

EPRI and Japan Share Breeder Reactor Studies

EPRI and the Central Research Institute of the Electric Power Industry (CRIEPI) of Japan have agreed to a joint research effort aimed at expanding their knowledge of liquid metal fast breeder reactors (LMFBRs). Such cooperation offers significant cost savings to both institutes and an improved understanding of LMFBR technology. The focus of much R&D throughout the industrialized world, LMFBRs use liquid sodium as the coolant and operate with high-energy (fast) neutrons to produce more nuclear fuel than they consume.

Four research programs cofunded by EPRI and CRIEPI are already under way. Two of these, inelastic analysis and sodium sloshing effects in large LMFBR vessels, are being conducted in Japan. The other two, flow coupler development and thermal-striping effects for LMFBR structural materials, are being carried out in the United States. Joint studies have also been initiated in such areas as seismic isolation, high-temperature concrete, and enhanced-core-support development.

Another joint program is investigating a new double-pool concept that has the potential for reducing LMFBR capital costs. Two basic component-dependent configurations exist for an LMFBR. One, called the loop system, locates the pumps, heat exchangers, and steam generators outside the reactor vessel. The other is the pool system, where primary coolant pumps and intermediate heat exchangers are contained within a larger vessel. The new pool concept places the reactor vessel, secondary coolant pumps, and steam generators into a second pool (hence the term *double pool*).

By reducing the amount of piping within the reactor and the size of steam generator and containment buildings, the double-pool design results in a more compact and efficient nuclear island configuration, which may lead to significant reductions in capital cost for the plant.

Japan and the United States have undertaken similar breeder technology development studies in the past. Currently, both countries have either initiated or recently completed loop and pool design activities for large, commercial-size plants, and each plans eventually to select a fundamental concept for future investigations. In addition to being counterpart utility organizations, EPRI and CRIEPI are participants in their respective countries' breeder technology activities. Consequently, they derive mutual benefit from continued communications and from pursuing endeavors of common interest.

Although the cooperative research between EPRI and CRIEPI emphasizes breeder topics, some of the emerging technology will apply to light water reactors and high-temperature gas-cooled reactors. Many reactor manufacturers and architect-engineers involved in U.S. and Japanese LMFBR programs are also participating in the EPRI–CRIEPI studies. The EPRI Consolidated Management Office for the LMFBR, in cooperation with the U.S. Department of Energy, is continuing efforts to expand areas of mutual interest with CRIEPI. ■

Test Tower Now Available for Loan

A mobile test facility for evaluating cooling-water treatment technologies is available to utilities through June 1987. Interested utilities can transport the facility to their own stations and conduct tests on various methods of treating cooling water to prevent condenser scaling.

In a power plant, control of cooling-water chemistry is essential for protecting the condenser from scaling, ensuring good condenser performance, and preventing costly maintenance shutdowns. During the last decade, however, rising costs for blowdown treatment, uncertain performance of water treatment methods, and stringent regulations on aqueous plant discharge have all created problems in the design of recirculating systems.

The EPRI field test facility tests the effectiveness of chemical softening methods for removing scale-forming constituents from the cooling water. These methods may prove more reliable and economical than methods based on chemical conditioning.

Utilities can use the facility to test cooling-water treatment methods without interfering in the operations of their existing cooling systems. And the facility uses the source water that is specific to a site, which allows for an accurate simulation of on-site conditions. The test facility includes a pilot-scale cooling tower, condenser, steam boiler, makeup and sidestream treatment, control system, and a computerized data acquisition system.

Two computer codes that support the system are also available to EPRI members. These codes, CLGTWR and DRIVER, help the user to evaluate treatment and operation alternatives, to improve and refine treatment methods, and to predict adverse chemical and process conditions in the plant cooling system.

The economies afforded by optimizing the treatment procedure are large. For example, a power plant using sidestream chemical softening of cooling water in place of mechanical distillation of cooling-tower blowdown can realize capital and operating levelized annual cost savings of up to 40% (that is, up to $0.5 million). These treatment approaches will also serve to improve cooling-water circuit chemistries and provide for proper management of a plant's water resources. The operating utility will be able to predict impending problems and identify appropriate corrective measures.

The facility is now at Sierra Pacific Power Co.'s North Valmy station in Nevada, the second site where it has been successfully used for field testing. Until June of 1987, when it is next scheduled for use, the facility is available at no cost to member utilities willing to transport it. For more information about the mobile test facility, contact Wayne Micheletti, EPRI project manager, (415) 855-2469. ■

Plasma-Fired Cupola Development

Early results from a 23-month test cofunded by EPRI and Westinghouse Electric Corp. are confirming the technical and economic benefits of plasma-fired cupola technology. The tests focused on the use of electric-arc plasma torches, rather than coke, to supply the heat needed for melting metals in cupolas, the vertical-shaft furnaces widely used in the foundry industry.

The $2 million project is being conducted at Westinghouse's 20-MW Plasma Test Center in Waltz Mill, Pennsylvania. Actual testing followed a successful 12-month effort to design and fabricate a unique 2.5-t/h test cupola fitted with a 1.5-MW Westinghouse Marc-11 plasma torch. Though relatively small, the commercial-size test unit, which started testing operations in November 1984, is equipped with facilities for handling both raw materials and hot metal.

Plasmas, produced from high-intensity electric arcs, can achieve temperatures in excess of 10,000°F (5400°C), far higher than the 2800°F (1400°C) practical limit obtained with fossil fuels. The ability of plasmas to supply this ultrahigh temperature independently of combustion can reduce hot metal costs by 10–30%, primarily because large quantities of inexpensive raw materials, such as loose cast iron borings and turnings, can be processed without briqueting.

Moreover, plasma heat can be introduced with a wide variety of gases, providing a greatly enhanced control over processing conditions and product quality. There also promises to be significant environmental benefits stemming from plasma technology, such as reduced gas effluent handling, because of its decreased dependence on fossil fuels. Other benefits derive from increased productivity; improved silicon yields; lower sulfur pick-up; and the ability to use sand, rather than expensive ferrosilicon, as a source of product silicon content.

In addition to EPRI and Westinghouse, Modern Equipment Co., a leading supplier of cupola technology to the foundry industry, and General Motors–Central Foundry Division (GM–CFD) are also participating in the project. Modern Equipment designed and fabricated the test unit and has applied its process evaluation expertise to the use of plasma technology in industrial cupola systems. GM–CFD has supplied a number of raw materials for the test program. ■

Utility Representatives Form Association

Applications of photovoltaics, municipal solid waste, and biomass are three renewable energy options that will receive top priority as the newly formed Utility Renewable Resources Association seeks ways to encourage the development of renewable resources technologies. URRA, which was formed in response to an increasing need by utilities to learn more about the applications of renewable energy resources, hopes to establish a consensus on the future direction of renewable resources development and to help utilities integrate applicable technologies into their own utility systems. So far, 14 utilities have joined URRA and have selected EPRI to be the association's first ex officio member.

URRA will coordinate the cooperative exchange of renewable resources information among the participating utilities. It will also help utilities develop system planning models that will allow them to adequately assess the electricity-generating potential of renewable energy technologies.

The scope of the association includes all renewable energy resource applications that have the potential of being incorporated into utility systems. Initially, however, URRA will concentrate on such direct solar energy applications as photovoltaics and solar-thermal conversion; on such indirect solar energy applications as wind, hydro, biomass, and municipal waste utilization; and on geothermal energy uses. For each technology that it examines, URRA will analyze utility requirements, planning strategies, and field experience from existing renewable resources power systems. Such studies, in addition to other technical and economic information, will help utilities assess how they can best commercialize renewable energy technologies for the production of electricity.

For further information concerning URRA, contact James Janasik, administrative manager, Advanced Power Systems Division, (415) 855-2486. ■

CALENDAR

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

SEPTEMBER

17–19
Industrial End-Use Forecasting Under Structural Change
Washington, D.C.
Contact: Ahmad Faruqui (415) 855-2630

20
Seminar: UPM Progress Report
Washington, D.C.
Contact: Lewis Rubin (415) 855-2743

OCTOBER

4
Seminar: UPM Progress Report
Chicago, Illinois
Contact: Lewis Rubin (415) 855-2743

7
Seminar: Coal Transportation Costing and Modeling
San Antonio, Texas
Contact: Edward Altouney (415) 855-2626

8–10
Seminar: Fuel Supply
San Antonio, Texas
Contact: Howard Mueller (415) 855-2745

8–10
Seminar: Voltage-VAR Projects of the Power System Planning and Operations Program
Philadelphia, Pennsylvania
Contact: John Lamont (415) 855-2832

9–11
Workshop: Fossil Fuel Plant Heat Rate Improvement
San Francisco, California
Contact: Frank Wong (415) 855-8969

18
Seminar: UPM Progress Report
San Francisco, California
Contact: Lewis Rubin (415) 855-2743

22–25
1985 PCB Seminar
Seattle, Washington
Contact: Gilbert Addis (415) 855-2286

22–25
Conference: Production Simulation (planning and operating issues; BENCHMARK)
Chattanooga, Tennessee
Contact: J. K. Delson (415) 855-2619

23–24
Symposium: Load Forecasting
San Antonio, Texas
Contact: John Chamberlin (415) 855-2415

24–25
Seminar: Technology Transfer for Solid-Waste Environmental Studies
Denver, Colorado
Contact: Ishwar Murarka (415) 855-2150

NOVEMBER

6–8
Workshop: Fossil Fuel Plant Cycling
Miami, Florida
Contact: Frank Wong (415) 855-8969

12–14
Conference: Fabric Filter Development and Optimization
Scottsdale, Arizona
Contact: Walter Piulle (415) 855-2470

R&D Status Report
ADVANCED POWER SYSTEMS DIVISION

Dwain Spencer, Vice President

AVAILABILITY ANALYSIS FOR GCC POWER PLANTS

The development of the Cool Water coal gasification–combined-cycle (GCC) electric generating unit, a forerunner of commercial units, has involved the extensive use of availability evaluation and prediction methods to ensure optimal unit availability. It is believed that the utility industry can beneficially take a similar approach in designing commercial units, each of which is likely to be different because of geographic conditions and the size and type of existing units. Thus EPRI initiated a project to consolidate in one document all the information a utility engineer will need to perform availability analyses (RP1800-1). The resulting document, Availability Analysis Handbook for Coal Gasification and Combustion Turbine–Based Power Systems, *is forthcoming (EPRI AP-4216). The use of the methods it presents—together with the UNIRAM computer code, which essentially eliminates computation requirements—will lead to better-informed decision making during design and review.*

The handbook developed in this project is comprehensive. It includes background material on availability analysis; discussions of, and references to, computer-based programs that facilitate computation; methods for developing data and for handling data uncertainty; and data on failure rates and repair rates, some based on experience and some on estimates, for the various components of GCC units. Because a GCC plant comprises a combined-cycle combustion unit, the data are applicable to studies of combined-cycle equipment as well. In addition, the methodology portions are sufficiently general to permit broader application to electric generating units other than GCC or combined-cycle units.

Availability prediction and allocation

The handbook deals with availability as a single integrated characteristic and with each of its two components: reliability and maintainability. Availability and equivalent availability are defined as they are in standard utility industry usage. Reliability and maintainability are defined somewhat differently than they are by the industry, however—in accordance with the way the terms are more widely used. Reliability is defined as the probability that a unit will operate without failure for a selected time period, and maintainability is defined as the probability that a repair will be completed within a certain time period.

Methods for performing reliability, availability, and maintainability (RAM) predictions or evaluations are described in detail in the handbook—from background material to application examples. For typical electric generating units, these analyses require extensive computation and consequently could entail considerable time and cost. To facilitate computation EPRI developed UNIRAM, a computer-based model that permits the user to perform the calculations in seconds at very low cost. This code is available to EPRI member utilities at no charge and to others at a moderate price reflecting actual development costs.

In addition to RAM prediction methods, the handbook describes methods for performing allocations and preparing criticality ranking lists. The allocation procedure enables the user first to set a target for availability (or a similar measure) for the unit or plant (or other entity), then to assign values to the components so that the overall goal will be met. The criticality procedure ranks components according to their impact on unit effectiveness, thereby providing insight into which components have the greatest impact. Although experienced operators are knowledgeable in these matters, the modern unit is so complex that nonlinearities and other variants do occasionally lead to results that significantly contradict experience. Also, when differences between components are small, the formal analytic procedure can help in determining the correct order and the degree of difference. The rankings enable the designer to compare the effects of differences in component quality or in configurations of components, on the one hand, with the costs involved, on the other.

Data sources and uncertainty

Data are often the key element in RAM analyses, as well as in allocations and criticality rankings. The ideal data are those a utility has collected on its own system because they reflect the special policies, environment, and infrastructure that affect the functioning of the equipment. Often such data are not available, however, and other sources must be used. These include sources associated with the utility industry—such as the Generating Availability Data System (GADS) of the North American Electric Reliability Council—and sources independent of the industry. Utilities occasionally (and with reason) find data from other sources suspect. Nonetheless, as long as consistency is maintained, such data, even data of questionable reliability, can be used in two situations that occur frequently.

The first situation involves analyses that are being performed to compare two or more alternatives (e.g., the present system and an improved system) for which no accurate data are available. In such cases, the possible error associated with uncertain data may be viewed as having the same effect on each alternative.

The second situation involves a comparison between (1) an existing component for which good data based on experience are available and (2) a new or proposed component for which no experiential data are available. In such cases, the user can analyze the effect of the "poor" (nonexperiential) data by using a range of values for the new component in repeated evaluations of the new configuration—in effect performing a sensitivity analysis. The new component may be used in such a way that changes in its quality have relatively minor impact. If the sensitivity is high (i.e., if minor changes have significant impact), a number of methods are available for upgrading the quality of the data. As discussed in Appendix A of the handbook, these range from models to consensus procedures. Also, Section 8 of the handbook presents a collection of data on GCC system elements, some obtained from standard sources and some derived from analysis and a consensus of experts.

Modeling

RAM models are different from process flow diagrams and many other types of representation structured to depict the physical or functional aspects of an entity. RAM models are intended to provide insights into the special availability aspects of the entity they represent and to facilitate the computation of associated measures. An example of a RAM model is presented in Figure 1.

To compute a system's RAM performance characteristics, the user must assign values to certain measures for each of the elements in the model; usually these measures are mean time between failures (MTBF), mean downtime (MDT), and the number of similar components needed for a specific level of production (e.g., two out of three coal-handling subsystems for 100% capacity). The calculus for availability computations is based on that of probabilities and differs from the calculus to which users are probably accustomed. It is presented in easy-to-implement form in the handbook (Appendix B and the main text).

The UNIRAM computer code provides considerable additional assistance. It helps the user structure the model and handle the data and performs the necessary calculations at great speed. A typical set of calculations for analyzing a single configuration takes about one second of computer time. Criticality rankings take longer and may require up to 10 seconds. UNIRAM enables the user to make changes to explore many "what if" possibilities quickly and at low cost.

The methods and data presented in the handbook had a significant influence on the design of the Cool Water GCC unit. As a result of availability analyses, a quench gasifier and a coal-grinding system were retained in the design, and several proposed changes and additions were not implemented because they did not appear to be cost-effective. The methods are suited not only to new designs and to GCC units but also to a variety of other applications. Several utilities have applied them in life extension analyses, availability improvement programs, and maintenance analyses for coal-fired, oil-fired, and other units. *Project Manager: Jerome Weiss*

NEUTRON EFFECTS ON FUSION SYSTEM MATERIALS

As now conceived, first-generation fusion power systems would produce 80% of their power in the form of 14-MeV neutrons, which would interact dramatically with the structural material used to contain the reactions. For example, atoms in certain parts of the energy transfer structure of a magnetic fusion power plant may undergo approximately 500 displacements during the average life of the plant. This compares with only a few displacements in a conventional light water reactor and possibly 50 displacements in a fast fission system or an inertial fusion system with thick liquid metal curtains. The national fusion program, recognizing the issue of neutron damage, is in the process of developing materials that can be shown to sustain limited damage in such applications. To highlight this issue and to make some contributions to quantifying neutron damage, EPRI initiated a study on selected materials—specifically 2¼ Cr–1 Mo ferritic steel, HT-9 ferritic steel, vanadium alloys, and copper alloys. These were selected because of their potential for greater radiation resistance, low long-term radioactivation, or high heat flux capability.

In a recent project to examine the data needs for improvement in fusion designs (RP1971), the need for information on fast-neutron damage of structural energy transfer systems was judged to be most critical. In addition, data on neutron damage of certain structural materials that have minimal neutron activation were lacking.

In cooperation with the Office of Fusion Energy of the Department of Energy (DOE), EPRI obtained samples of vanadium and ferritic steel

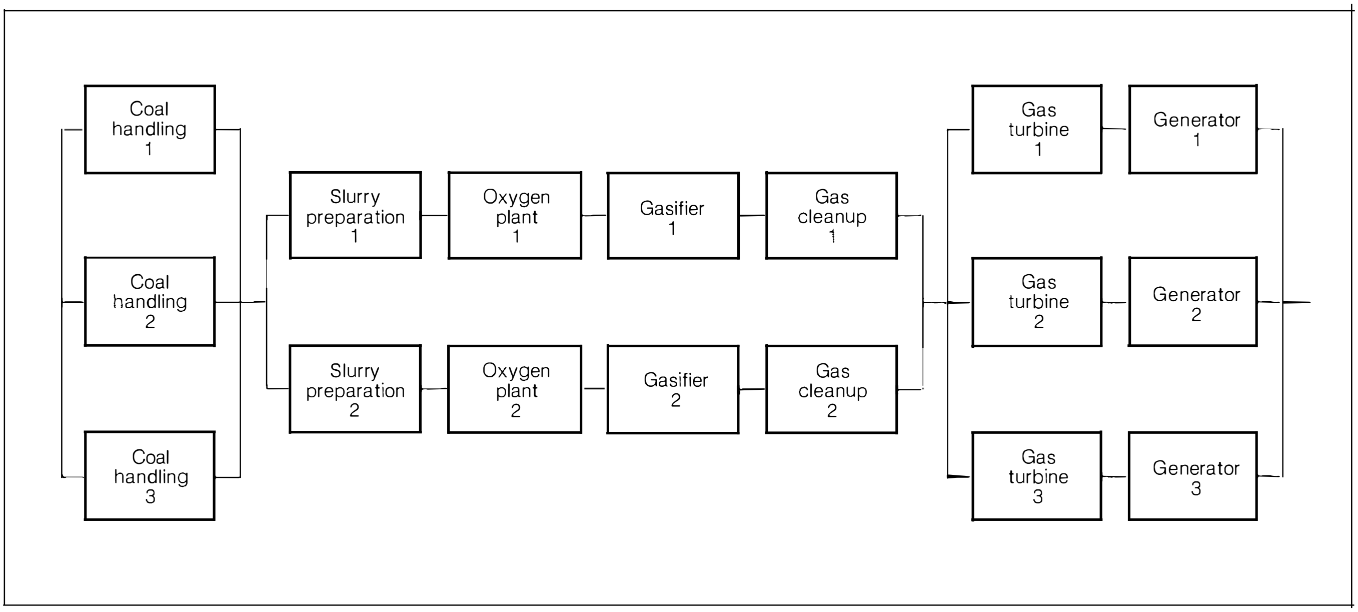


Figure 1 Availability block diagram for a GCC unit. Such diagrams are used in RAM analyses to develop the relationships between components in terms of availability and to facilitate the computation of availability performance characteristics. Unlike process flow diagrams, from which they are derived, availability block diagrams do not show the exact physical relationships between elements. In a process flow diagram, for example, the oxygen plant would be a separate input to the gasifier, not connected in series after the slurry preparation equipment. The oxygen plant is serially connected here because its availability is essential for gasifier operation—that is, if the oxygen feed fails, the gasifier cannot operate and the condition of the other equipment is immaterial.

alloys that had been irradiated in DOE facilities and examined them in a study to provide engineering data for the analysis of fusion reactor components (RP1597); this study also focused on developing a fundamental understanding of the effects of neutron irradiation on the material properties of vanadium and ferritic alloys. Later, samples of copper alloys were added because of the renewed interest in small compact fusion systems and the obvious need for data on copper exposure to very fast neutrons, which occurs in most fusion designs.

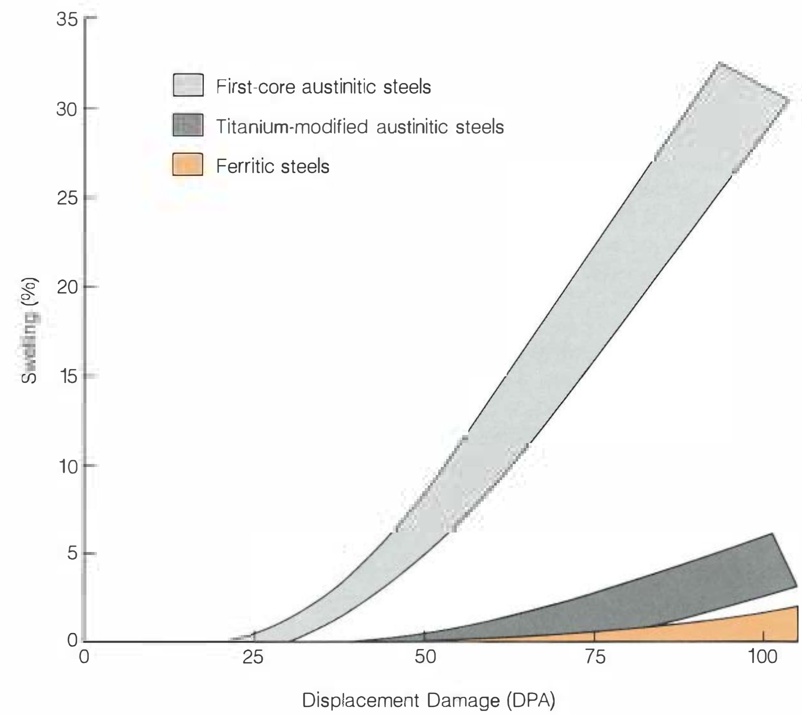
To minimize the project cost, researchers were very specific about which alloys were to be tested. In addition, the study used preirradiated archive samples supplied by DOE, and the experimental data were carefully coordinated with the materials modeling personnel and the fusion system designers. The team met periodically to ensure that the data produced would be useful.

Ferritic steels

Ferritic steels, particularly martenistic steels containing 9–13% chromium, have been considered for use in the cladding and ducts of fast breeder reactors because of their creep resistance, strength at elevated temperatures, compatibility with liquid metal coolant, and industrial availability. These steels are also of interest to fusion system designers for the same reasons. Initial examination of irradiation data from both breeder and fusion research indicates that the 9–13% chromium alloys (such as HT-9) may offer longer component lifetimes than the austenitic steels (such as PCA) because of their relative resistance to swelling (Figure 2). Unfortunately, the majority of the irradiation data are for doses less than 100 displacements per atom (DPA). Therefore, a project was initiated to examine the damage of ferritic alloys at higher doses—in particular, the lower-chromium alloy 2¼ Cr–1 Mo.

Although the 2¼ Cr–1 Mo alloy was selected for several inertial fusion designs, the lower-chromium alloys have generally not been considered for magnetic fusion designs because of their lower creep strength at temperatures above 500°C. However, because recent magnetic fusion power plant designs have a specified maximum structural temperature of 500°C, the lower-chromium steels may become a viable alternative for magnetic fusion, offering the prospect of better weldability. The higher-chromium steels, such as HT-9, are more sensitive to cold cracking in the heat-affected zones of welds than are the lower-chromium steels, such as 2¼ Cr–1 Mo. For the large complicated structures specified for fusion designs, which are likely to require a number of welds, improved weldability could be a distinct advantage.

Figure 2 The significantly higher resistance to swelling of body-centered cubic ferritic steels over face-centered cubic austenitic steels in the 500–650°C temperature range suggests longer lifetimes for ferritic steel components in fusion applications.



The high-dose irradiation project covered three areas of investigation: microstructure, mechanical properties, and liquid metal embrittlement. The microstructure studies, conducted at the Hanford Engineering Development Laboratory and the University of Wisconsin, used materials provided by the Office of Fusion Energy. The two heats of materials examined had undergone different preirradiation heat treatments: one was treated to a peak fluence of 25 DPA and the other to 100 DPA. Both these materials were irradiated in the EBR-II reactor over the temperature range of 390–510°C.

Irradiation produced small amounts of void swelling, precipitation, and dislocation network development at temperatures 480°C or below. At 500°C and above, behavior could best be described as precipitate overaging. Void swelling varied as a function of irradiation temperature, preirradiation microstructure, and possibly heat treatment or composition differences; peak swelling on the order of 0.5% was found following irradiation at 400°C.

Detailed examination was made of the higher-fluence microstructure to quantify the relationship between the defect morphology and the metallurgical structure (ferrite, upper bainite, or lower bainite). Results of this examination revealed that for a 400°C specimen with average bulk swelling of 0.12%, the amount of swelling observed in the ferrite grains was 0.22%, the amount in the lower bainite was 0.06%, and in the upper bainite, 0.05%. This first attempt at quantifying the radiation-induced defect structure by phase indicates that it may be possible, at least in this alloy system, to control swelling by appropriate heat treatment.

The University of Wisconsin performed ion irradiation on an archive 2¼ Cr–1 Mo alloy sample used in the earlier neutron irradiation studies. Initial ion irradiation was limited to the same DPA levels as the neutron irradiation (but without helium) to evaluate the differences in time/temperature exposures between the neutron and ion irradiations. Ion irradiations were then extended to hundreds of DPA. Essentially no voids were observed under these conditions. However, ion irradiation drastically changed the microstructure and dislocation structure and converted the bainite structures to ferrite; this structural modification was first noted in the neutron irradiation study. When helium atoms were preinjected into the surface to a depth of 1.5 μm, the alloy with helium developed a stable substructure that did not disappear with further ion irradiation. The alloy region injected with helium exhibited a small amount of swelling that was quite heterogeneously distributed.

The effect of neutron irradiation on the tensile properties of normalized and tempered 2¼ Cr–1 Mo steel was determined by Oak Ridge National Laboratory on specimens also provided by the Office of Fusion Energy. The specimens were irradiated in the EBR-II to 9 DPA and 23 DPA and tested (Figure 3). The results were compared with those for unirradiated control specimens and specimens that had been aged at the same temperatures as the irradiations for an equivalent amount of time (5000 and 10,000 h).

Irradiation at 390°C for 5000 h produced an increase in both yield and ultimate tensile strengths, along with a corresponding decrease in uniform and total elongation. At 450, 500, and 550°C, the irradiated specimens showed lower strength than the unirradiated control specimens. The strength of the irradiated steel at 450 and 500°C was close to the values for the specimens aged at these temperatures, while at 550°C, the strength of the irradiated steel was considerably below that of the aged material. In all cases, little difference was observed between specimens exposed to low and higher irradiation doses.

The strength changes produced by irradiation were attributed partly to the irradiation-induced dislocation structure resulting from displacement damage and partly to the radiation-enhanced precipitation that was observed.

Vanadium and copper alloys

Vanadium alloys are of interest in fusion system design because they exhibit higher elevated-temperature strength, better corrosion resistance in pure lithium, and better thermal and physical properties than other candidate structural materials. An additional benefit is that vanadium alloys have the lowest residual radioactivity of all the current candidate alloys, thus reducing the long-term storage requirements. Very limited experience, derived totally from fission reactor irradiation and ion simulation studies, indicates that vanadium alloys, particularly those containing titanium additions, are resistant to gross swelling and do not appear to become severely embrittled by neutron irradiation. These conclusions are tentative because the data base is sparse and the bulk of the information is for the V–20 Ti alloy.

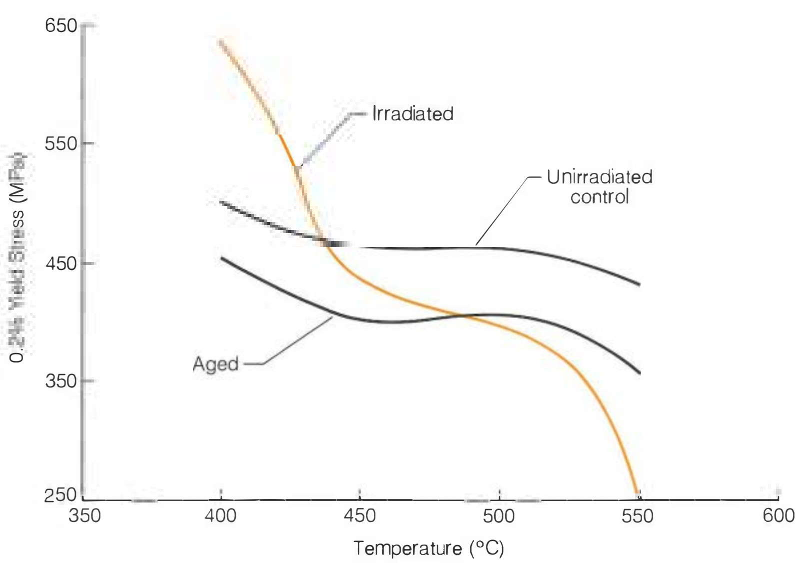


Figure 3 Investigation of neutron irradiation effects at Oak Ridge National Laboratory included this test of the 0.2% yield stress of 2¼ Cr–1 Mo steel for irradiated, aged, and control specimens. The aging temperature for the aged specimens was matched to the irradiation temperature for the irradiated specimens; aging and irradiation periods were both 5000 h.

Currently, the V-Cr-Ti ternary alloys have been identified as the leading candidates for the vanadium class of alloys because of their creep strength and low activation potential. Within the V-Cr-Ti class, the V–15 Cr–5 Ti alloy appears to be a good choice on the basis of its unirradiated tensile creep, fatigue properties, and weldability. Unfortunately, before the EPRI study, no irradiation data were available for the alloy, forestalling a judgment on its suitability for fusion. However, specimens were available that had been irradiated to roughly 5 DPA over a temperature range of 375 to 600°C. DOE was willing to make them available to EPRI for tests.

Westinghouse Electric Corp. was selected to evaluate this alloy because of its experience in developing vanadium alloys for fast breeder reactor research. The evaluation of the DOE specimens included tests on hardness and microstructural examination. The tensile tests were conducted at room temperature, at the irradiation temperature, and at 100°C above the irradiation temperature.

The results showed a severe loss of ductility. Tensile ductility of all specimens tested below the irradiation temperature was negligible, and all fracture surfaces showed brittle transgranular cleavage. Testing of the unirradiated specimens at room temperature resulted in ductilities greater than or equal to 9%, with the fracture surfaces revealing both mixed cleavage and ductile processes, which is common for the alloy.

To assess whether or not impurity segregation was contributing to the brittle behavior of the specimen, researchers examined several specimens by auger electron spectroscopy (AES). The specimens were fractured by impact loading in situ in the AES chamber at room temperature. Both the irradiated and unirradiated specimens fractured by transgranular cleavage. Examination of the fracture surfaces immediately after fracture revealed the presence of vanadium, titanium, oxygen, and nitrogen. However, the most remarkable aspect of the analysis was the finding of sulfur on the fracture surfaces in concentrations of several percent.

Sulfur is typically not reported in refractory metals because it tends to occur in low concentrations, usually less than 0.02 wt%. Although subsequent analysis of the material at Argonne National Laboratory verified the sulfur findings, sulfur cannot be identified as the primary contributor to the loss of ductility of the irradiated specimens because the unirradiated ductile material had roughly the same concentration of sulfur at the fracture surface as the irradiated brittle material. There may be a synergistic relationship between the segregated sulfur and the interstitial elements, such as oxygen or nitrogen. It is interesting to note that subsequent to this investigation a second set of samples from the same heat of material gave roughly the same findings.

For the copper tests, three alloys were irradiated with 28-MeV Si^+ ions by the University of Pittsburgh for Westinghouse. An Amzirc alloy and a dispersion-hardened copper alloy (Al-60) were obtained from archived heats used in neutron irradiation experiments at Los Alamos National Laboratory for fusion, and Cu-Be-Ni samples were obtained from International Nuclear Energy Systems Corp. These three alloys were irradiated to levels of 10–20 DPA at temperatures ranging from 250 to 500°C.

The two copper-based alloys that showed promise of meeting the near-term needs of fusion research were Cu-Be-Ni and Al-60. These alloys had good microstructural stability from 250 to 350°C and showed only a slight tendency to swell in transgranular bands, with swelling of approximately 0.01%/DPA at 300–350°C. The Amzirc showed 1–5% swelling per DPA in this temperature range. These observations, using ion irradiation, give only preliminary information; they do provide, however, a means of early alloy selection, to be followed by more extensive tests with neutron irradiation.

Theory and modeling

In conjunction with the effort to obtain data on ferritic, vanadium, and copper alloys, the EPRI project also supported theoretical modeling of the swelling of ferritic alloys under experimental investigation. Using new experimental techniques and the recent understanding that the basic cause of swelling is preferential absorption of the produced interstitial atoms at dislocations, the EPRI project team has made a significant contribution to the understanding of swelling resistance in different alloy systems.

Radiation-induced void formation and growth depends on many metallurgical factors. In particular, most metals require a minute but essential amount of surface-active elements or insoluble gases for voids to nucleate. In future fusion reactors, the high helium production through (n, α) reactions will ensure that voids form readily. The essential question then remains how rapidly they will grow after their nucleation—and this depends on the aforementioned bias for preferential interstitial absorption.

The theoretical research carried out for EPRI has now revealed a fundamental difference in the bias of alloys that depends on their crystal structure. Such alloys as austenitic stainless steels possess a face-centered cubic structure, which is associated with a large bias; as a result, it was predicted that all alloys with this crystal structure are capable of void swelling at maximum rates of 1–3%/DPA. Specifically, austenitic alloys were predicted to swell at a rate less than or equal to about 1.4%/DPA. The observed rates were found to be around 1%/DPA, confirming the theoretical predictions. In contrast, alloys and metals of the body-centered cubic structure were predicted to swell at maximum rates of 0.1–0.3%/DPA. The importance of this fundamental discovery is that ferritic steels indeed possess a much greater swelling resistance than austenitic stainless steels.

The maximum swelling rate, being an intrinsic property of the crystal structure, is realized only when the metallurgical microstructure reaches an optimal state of parity—generally stated, when dislocations and voids coexist in equal abundance. One can influence the microstructure and its evolution during irradiation by metallurgical processing, by judicious addition of alloying elements, and by appropriate selection of the irradiation temperature. In this manner, a state of microstructural parity can be avoided, reducing the swelling rate below the intrinsic maximum value.

The results of the experimental and theoretical work on 2¼ Cr–1 Mo steel sponsored by EPRI supplied such input as equations for modelers charged with providing design information on 2¼ Cr–1 Mo steel undergoing neutron irradiation in the 400–500°C range.

The fusion materials projects identified 2¼ CR–1 Mo ferritic steels as leading candidates for high neutron fluence nuclear subsystems and alerted the nuclear community to the need for further neutron irradiation work on vanadium alloys. In addition, two copper alloys were identified as reasonable candidates for high neutron fluences materials and a predictive model was developed to describe radiation-induced swelling of steels. The project management approach, which brought the experimentalists, designers, and modelers together for periodic review, may serve as an appropriate way to address future materials selection. *Program Manager: Robert Scott*

R&D Status Report
COAL COMBUSTION SYSTEMS DIVISION

Kurt Yeager, Vice President

DIAGNOSTIC MONITORING OF FOSSIL FUEL PLANTS

Increasingly, utilities are seeking ways to improve the availability of aging fossil fuel plants. One approach with significant potential for increasing availability is the on-line monitoring of key components and systems. The primary purpose of on-line monitoring systems is to reduce plant downtime by detecting and diagnosing mechanical abnormalities at an early stage. In many cases, operators using this information can avoid forced outages and schedule repairs when power demand is low. Maintenance personnel can use this information to determine the maintenance to be performed and to ensure that they have the necessary parts and tools ready when the equipment is taken out of service.

On-line diagnostic systems for fossil fuel and nuclear power plants are generally based on microprocessor systems, which automatically track parameters of interest and flag abnormal situations. EPRI's approach in developing such systems has typically been to install and evaluate a prototype for an extended period of time in a host utility's plant before the system is released as a package to the industry. Table 1 lists some of the major utility demonstrations of plant diagnostics and their potential payback. These systems will significantly improve plant availability, as evidenced by better maintenance planning and a reduction in forced outages. Averting a failure or unanticipated outage of even a single day can easily offset the investment in such a system, as can be seen in Table 1.

Boiler monitoring

The majority of plant availability losses can be attributed to boiler-related failures, with tube leaks alone causing 6% boiler unavailability. EPRI is developing devices for detecting tube leaks in the early stages, before steam impingement or flow starvation results in damage to adjacent tubes. Sensitive microphones are used to detect pinhole leaks acoustically—perhaps three to five days earlier than standard methods of detection. These sensors can also indicate the location and growth rate of the leak (RP1863-2).

Devices for tracking damage and wear in critical components are being demonstrated in other projects. A boiler thermal stress and condition analyzer monitors critical headers, drums, and main steam lines (RP1893-1). The analyzer monitors thermal stresses produced by high temperatures or pressures, evaluates cumulative creep/fatigue damage, and calculates life expenditure. Another device, a wear monitor, under development by Spire Corp., is based on a novel technique. By transmuting a few small areas of a component subject to wear, gamma rays can be detected from the partially activated component (RP1893-2). As the component surface wears, the monitored radiation is reduced proportionately. For example, a bearing in the boiler circulating pump at a Kansas Power & Light Co. plant is being monitored through an 8-in (20-cm) steel casing. Utilities can use these devices for maximizing boiler life and projecting optimal maintenance intervals.

Rotating equipment monitoring

Utility data reveal that an average of 40% of all fossil fuel power plant forced outages are caused by failure of the rotating equipment: fans, pumps, and turbine generators. Early detection of incipient failure would allow for optimal maintenance and spare parts planning and prevent catastrophic failure, which is always a possibility with high-speed rotating components. One method of predicting impending failure recognizes that changes in the vibration spectra with time can often be related to a specific failure mode, such as unbalance, blade rubbing, bearing deterioration, oil whip, steam whirl, shaft bowing, or cracking. These symptoms can be sensed and diagnosed automatically by a dedicated computer. This technique, commonly referred to as vibration signature analysis, can be applied in varying levels of sophistication to rotating equipment. EPRI has been exploring such methods for several years and is now engaged in establishing predictive maintenance systems based on continuous vibration signature analysis.

Continuous monitoring and trending of the vibration spectrum, as opposed to periodic snapshots of bearing vibration levels, provides several advantages.

- The spectrum can be analyzed. Because a number of failures, particularly in the early stages, appear as amplitude changes at frequencies other than running speed (60 Hz), analysis of the complete spectrum is essential for early detection.
- Vibration and process data are continuously monitored and interrogated, providing the earliest possible warning of a failure condition. The historical record maintained by the computer assists in rapid diagnosis of the signal deviation.
- A baseline signature characterizing normal vibration response to equipment operation, such as changes in load, speed, or temperature, can be determined. This understanding of normal vibration variation is the key to discerning trends caused by incipient failures.

A contract with Radian Corp. has produced a prototype predictive maintenance system for major plant rotating machinery (turbine generators, major fans and pumps) based on vibration signature analysis (RP1864-2). In recognition of the necessity for such a system to correctly interpret normal variations in vibration amplitude and frequency, this project is founded on a strong statistical base of data relating such factors as vibration and load, speed, and temperature. Model development is still under way to factor in the long-term influences, such as seasonal changes in back pressure and ambient air temperature, which occur over weeks or months. The system at New Haven Harbor, a fully functional continuous monitoring system, contains all the elements a utility needs to introduce vibration signature analysis into a predictive maintenance system.

Advanced vibration monitoring systems

An advanced version of the New Haven Harbor project recognizes that a computer model of an elastic rotor-bearing system can be instrumental in predicting the vibration pattern at one axial location caused by an anomaly or disturbance at another. Shaker Research Corp. is validating this technique for EPRI, which goes one step beyond the New Haven Harbor system (RP1864-1). The site for the three-year project is the Eddystone plant of Philadelphia Electric Co.

In this system, an analytic rotor dynamics model of each piece of rotating machinery will be stored in the computer. The models will be accessed as necessary to interpret measured vibration data. The Eddystone system, scheduled to be in operation by mid 1986, will provide the ability to quickly locate the source of a problem, in addition to increasing the confidence with which specific shaft problems can be diagnosed.

Axial fan monitoring

A continuous monitoring system of a special type has been implemented by Battelle, Columbus Laboratories on six axial fans—one pair each of primary-air, forced-draft, and induced-draft fans—at the Homer City generating station of Pennsylvania Electric Co. (RP734-4). In this system high-frequency (>20 kHz) vibration transducers, installed on the rolling element bearings, measure the effects of pits or spalls produced as the rollers wear. Over the past year of monitoring, one bearing failure has occurred. Preliminary analysis of the data shows that measurement of acceleration at frequencies above 20 kHz is an effective technique for detecting failures in antifriction bearings. Over the next 12 months, we expect to obtain additional data on various failure modes and degrees of degradation. A correlation will then be developed between remaining bearing life and the high-frequency vibration signature to be used for future on-line diagnostic monitoring.

Laser-based systems

Instrumentation in hostile environments, such as on turbine shafts, steam lines, or generator high-voltage bushings and leads, can be particularly difficult. In these high-temperature, high-speed, or high-voltage environments, where conventional sensors would be short-lived, vibration can be readily measured with a laser Doppler sensor (General Electric Co., RP1855). The laser system, which detects light scattered by a vibrating component, requires only a line of sight and is capable of making measurements from as far away as 50 ft (15 m). Thus, the need for instrumenting the machine during a planned or forced shutdown is averted, resulting in avoidance of replacement power costs.

As part of the validation program, the laser system has been applied to the following.

- Monitoring torsional shaft vibration during a General Electric factory test of a generator rotor
- Diagnosing flange bolt failures from main steam line vibration at Allegheny Power System, Inc.'s Fort Martin plant and Pennsylvania Power & Light Co.'s Montour plant

Table 1
PLANT DIAGNOSTICS: MAJOR UTILITY DEMONSTRATIONS IN PROGRESS

Problem	Technique	Utility/Plant	Full/Partial Forced Outages (per year)*	Average Duration of Full Forced Outage (h)*	500-MW Replacement Power per Outage ($000)	Diagnostic System Cost ($000)
Turbine cracking	Acoustic emissions; vibration signature analysis	TVA/John Sevier	90	984	6200	100
Blade vibration	Acoustic emissions; Doppler sensor	Westinghouse Electric Corp.	270	708	4400	40
Generator arcing	Radio frequency signal detection	Texas Utility Generating Co.	40	386	2400	25
Turbine water induction	Ultrasonic sensors	Pennsylvania Electric Co./ Homer City	15	363	2300	200
Turbine or boiler erosion/corrosion	Radioactive decay (thin-layer activation)	Dayton Power and Light Co./ Stuart	1660	80	500	40
Tube leaks	Acoustic emissions	Baltimore Gas and Electric Co./Wagner	5230	65	406	90
Vibration in hostile regions (high speed, high voltage, high temperature)	Laser detection	Allegheny Power Co./ Fort Martin	880	58	362	50
Boiler creep/fatigue	Stress analysis	Consolidated Edison Co. of New York/Ravenswood	30	54	338	200
Rotating machinery failure	Vibration signature analysis with rotor dynamics	Philadelphia Electric Co./ Eddystone; United Illuminating Co./New Haven Harbor	8730	43	269	300
Draft fan failure	Vibration/acoustic emission sensors	Pennsylvania Electric Co./ Homer City	2190	33	206	50

*From the Generating Availability Data System of the North American Electric Reliability Council.

- Monitoring boiler pendant tubing and feed-pump vibrations at the General Electric power plant in Schenectady, New York

- Surveying vibration in the generator, including frame, shaft, bearings, and exciter brushes, at Tampa Electric Co.'s Big Bend plant

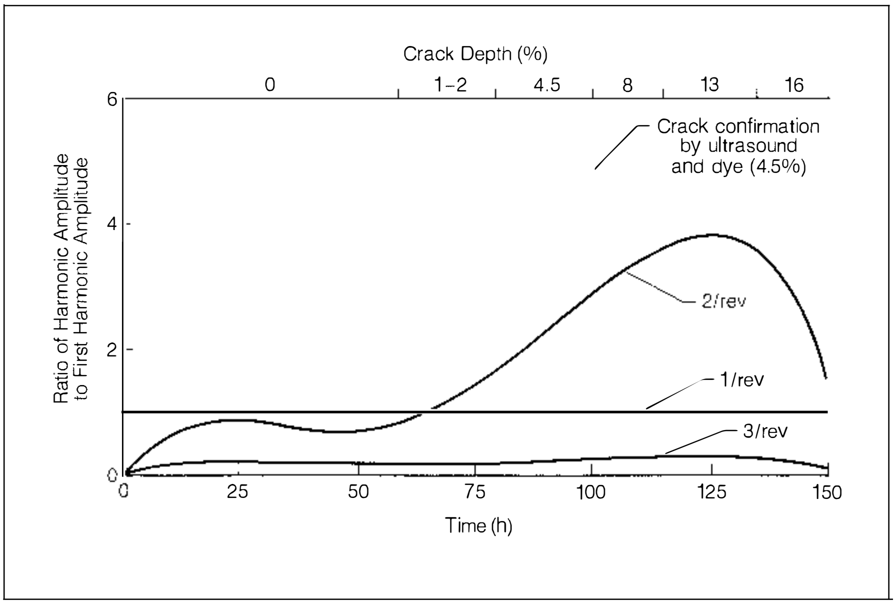
Such applications illustrate the wide range of potential applications for noncontacting, laser-based monitoring devices.

Diagnosing shaft cracking

A special concern relates to the fracture of the turbine generator drive train with its potential for catastrophic damage. Serious cracks have been detected in operating power plants in Europe and the United States. These cracks are often discovered during rundown in speed, when the vibration spectra show increasing response at critical speeds. Crack diagnosis by using vibration signatures may be possible at full-speed, full-load conditions, which is a more tenable method of monitoring and avoids replacement power costs.

To demonstrate this, transverse cracks are being grown on a 6-in (15-cm) diameter rotating shaft (Figure 1) at General Electric (RP1862). Computer analyses trend and diagnose vibration measurements along the shaft system. Test data clearly indicate the rise in the second-harmonic (2/rev) amplitude (Figure 2). This is a result of the process of crack opening and closing, which changes shaft stiffness twice each revolution. The new vibration analysis, using a unique data enhancement technique, detected the presence of a crack through only 2% of the rotor diameter before even dye penetrant or ultrasonic tests could identify it—a remarkable achievement. This system is now ready for field application to determine how the method is affected by turbine generator background noise. Subsequently, this technique will be incorporated in the New Haven Harbor and Eddystone monitoring systems.

Figure 2 Vibration histogram data on the growth of a transverse crack. General Electric Co.'s fatigue machine cracking was detected even before ultrasonic testing or a dye penetrant could identify the failure.



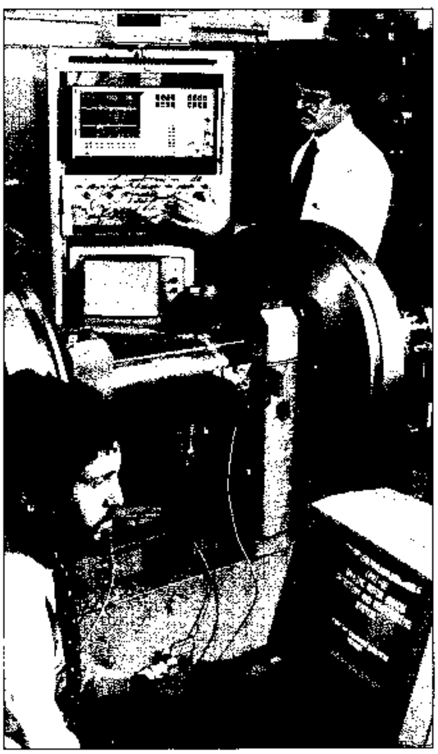


Figure 1 Rotating-shaft fatigue machine at General Electric Co., used to simulate transverse crack growth in turbine rotors. In the foreground is the vibration signature analysis system; the eddy-current crack monitor, shown in the background, images surface cracking.

Other methods of detecting shaft cracking are also under development. For example, direct imaging of known or suspected crack locations (using eddy-current sensor arrays or infrared techniques) can expose very tight surface-connected cracking that is only a few mils in width. The eddy-current system shown in Figure 1 monitors surface crack growth on shafts, couplings, blades, disks, or wherever the sensor can be located (RP1894-1).

Infrared methods that use a laser to locally heat the shaft surface are being researched by Arizona State University (RP1957-2). The infrared detector senses the temperature rise that results when a crack impedes the transfer of heat. This method has been successful in laboratory trials and is being developed further to distinguish surface blemishes from cracking. In fact, the detector is so sensitive that laser heating may not be necessary. Changes in surface emissivity and differences in infrared radiation due to cracking are apparent even at ambient temperatures.

The outlook

An EPRI-sponsored conference on incipient failure detection is held every two years to discuss progress in utility diagnostic programs and to present information on promising condition-monitoring techniques under development. Such conferences also provide input to EPRI R&D (CS-2920). The 1984 Orlando conference, which attracted 200 industry representatives, revealed that many utilities are setting up predictive maintenance programs, focusing initially on periodic vibration monitoring. Future work at EPRI will emphasize general guidelines for monitoring systems; interpretation of vibration signature data; integration of vibration systems with acoustic, stress, temperature, and other monitoring techniques; and reporting of diagnostic case histories.

EPRI is now structuring a plantwide demonstration and evaluation of condition-monitoring devices for fossil fuel units (RP2817), and an RFP will be issued soliciting a host site. The selected unit will serve as a test-bed for new sensors, instruments, and computer-based predictive maintenance systems. Monitors will be installed for the detection of such conditions as creep/fatigue damage in the piping and casings of heavy-walled components, generator arcing, torsional shaft vibration, water induction, boiler and turbine corrosion/erosion, lube oil contaminants, boiler tube leaks, steam whirl, oil whip, bearing deterioration, blade rubbing, and shaft cracking. In this manner, the full benefits of diagnostic monitoring can be demonstrated in one utility plant predictive maintenance program.

This project will involve a utility steering committee that will guide the project team in the selection of monitoring devices and to aid the commercialization of resulting products to the utility industry. *Project Manager: John Scheibel*

IN-FURNACE SO_2 CONTROL FOR PULVERIZED-COAL BOILERS

The concept of injecting calcium-based alkaline sorbent materials directly into the furnace of coal-fired utility boilers to reduce sulfur dioxide (SO_2) emissions is the subject of major research and development programs in the United States and abroad. EPRI is contributing to these efforts by sponsoring a test program to develop an understanding of fundamental process chemistry and to optimize the process for maximum SO_2 removal and calcium utilization. Complementary EPRI projects address engineering system design, economics, and power plant integration issues. These projects will provide the technical basis for designing and operating prototype furnace sorbent injection systems for 50–150-MW utility boilers, which is the next step toward commercialization.

The furnace sorbent injection process is based on the injection of pulverized calcium-based sorbent materials, such as limestone or calcium hydroxide, directly into the furnace cavity of a coal-fired boiler. When exposed to furnace temperatures, the sorbent rapidly decomposes to form reactive lime particles, which capture SO_2 in suspension to form particles of calcium sulfate. The flue gases carry this calcium sulfate, along with any unreacted lime, out of the furnace, where the particulate control device collects them with fly ash. In essence, this process attempts to apply to coal-fired boilers an SO_2 control technique similar in overall chemistry to that used in fluidized-bed boilers.

EPRI is developing this technology because of its potential as a cheaper incremental SO_2 control approach for existing power plants. Evidence shows that the process can reduce SO_2 emissions by 50% or more in utility retrofit applications at significantly lower capital cost than conventional flue gas desulfurization systems. If successfully developed, this process would increase utility flexibility for complying with SO_2 control, especially in the event of new legislation regulating SO_2 emissions from older, currently uncontrolled power plants. The lower capacity factors and remaining lives of these plants typically favor a less-capital-intensive technology. In addition to potential retrofit applications, this process may be integrated with other supplemental controls in the future for an overall SO_2 control capability adequate to meet stricter requirements in new plants.

A number of development issues form the basis for EPRI's furnace sorbent injection R&D projects. SO_2 capture itself is a complex physical and chemical process that is influenced by a variety of factors: sorbent properties, boiler temperatures and residence times, sorbent mixing and dispersion within the furnace, and coal composition. Engineers must understand the role that each of these variables plays in determining SO_2 removal before they can design optimal processes for the variety of site-specific utility applications. A major development issue in this regard is identifying an economical means for improving calcium utilization and thereby minimizing the quantity of sorbent required. Currently, calcium utilization is relatively low (typically between 15% and 40%), which results in most of the sorbent passing through the boiler unreacted. Increased calcium utilization will further improve the economic advantages of the process because sorbent is a major factor in the total cost of application.

Another issue is the potential impact the process will have on boiler and plant performance and operation, which might include fouling, corrosion, and slagging; problems of excessive particulate emissions; or increased waste management difficulties. A new unit can be designed to minimize such problems; in retrofits, they may be serious. Improved calcium utilization will minimize these effects.

These issues make the cost of commercial application somewhat uncertain. In addition to EPRI's technical goals, an important objective is to provide realistic cost estimates for utility boiler applications and to refine these estimates as the development efforts proceed.

Process development

EPRI is conducting a project to develop the furnace sorbent injection process with the participation of Southern Company Services, Inc. (RP2533-1). The project consists of pilot-scale tests, complemented by international information exchanges, fundamental process modeling and bench-scale studies, and a conceptual design for a 50-MW retrofit application. A major goal of the project is to understand the mechanisms that control sorbent utilization and to define methods for increasing sorbent reactivity and maximizing SO_2 removal. Therefore, a comprehensive analytic effort to characterize in detail the chemical and physical properties of fuels and raw and reacted sorbents will support the bench- and pilot-scale experiments. Several contractors are providing the broad range of technical capabilities and research facilities required for this effort: Southern Research Institute; KVB, Inc.; Fossil Energy Research Corp.; and the International Flame Research Foundation.

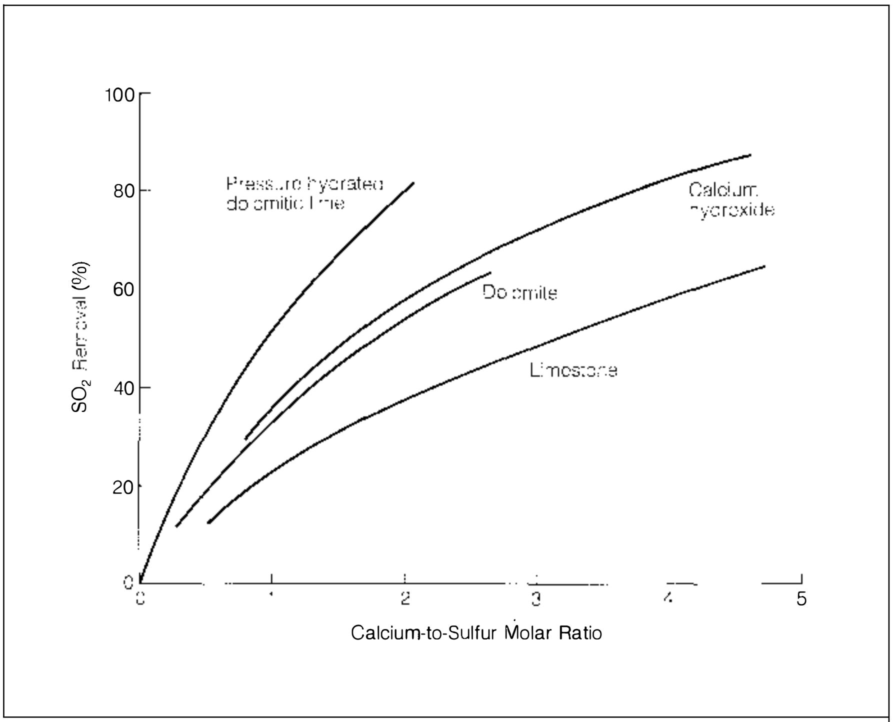
To assess the relative performance of different types of commercial calcium sorbents, extensive pilot testing at scales of 0.5 and 1.0×10^6 Btu/h has been completed on 3% sulfur bituminous coal with two varieties of limestone (calcium carbonate), a conventional hydrated lime (calcium hydroxide), and a pressure-hydrated dolomitic lime (calcium and magnesium hydroxides). Limited comparative tests were also performed with dolomite (calcium and magnesium carbonate).

Figure 3 compares the performance of these sorbents in the 1.0×10^6 Btu/h pilot test furnace. The SO_2 removals shown are representative of optimal values for each sorbent. For any given sorbent injection rate (as defined by the calcium-to-sulfur molar ratio, Ca/S), there is a considerable variation in SO_2 removal efficiency over the range of sorbent types tested. For example, at Ca/S = 2.0, the SO_2 removals range from about 30% to 80%. These removals correspond to calcium utilization efficiencies of 15–40%, relatively low compared with the calcium utilization achieved by conventional flue gas desulfurization. It should also be noted that although increasingly higher SO_2 removals can be achieved as Ca/S is increased, practical considerations of sorbent costs, boiler deposit rates, particulate emissions, and solid-waste disposal will probably dictate a maximum Ca/S value between 2 and 3 in most full-scale applications.

The hydroxides removed more SO_2 than did the carbonates, and for both the hydroxides and carbonates the dolomitic materials performed best. However, the dolomitic sorbents' greater SO_2 removal may be offset by their lower calcium content. Because of the presence of inert magnesium in the dolomitic sorbents, the quantity (lb/h) of these sorbents necessary to capture a given amount of SO_2 is about the same as the quantity of nondolomitic sorbent required to achieve a similar SO_2 removal. Although the magnesium does not itself remove SO_2, its presence appears to enhance calcium use.

The furnace gas temperature at the point of sorbent injection is the most important variable in determining how much of a given sorbent is used. A peak in SO_2 removal is evident for the various sorbents in a narrow temperature

Figure 3 Pilot tests comparing SO_2 removal with four types of calcium sorbent under optimal sorbent injection conditions with 3% sulfur bituminous coal. Flue gas temperature at the point of injection was near 2200°F (1200°C), corresponding to the thermal environment in the upper radiant zone of a coal-fired utility boiler.



range between 1800°F and 2200°F (980–1200°C). At higher temperatures, low SO_2 removal results from the reaction product's instability or the sorbent's rapid deactivation, caused by sintering. At temperatures below 1800°F (980°C), reactions are slower, and incomplete calcination may result in insufficient SO_2 capture in the reaction times available. The optimal temperature would typically occur in a furnace's upper radiant zone and leading convective sections. This orientation makes the section above the flame zone and burner region the preferred injection site in most applications.

Another important parameter governing SO_2 capture efficiency is the rate of change in flue gas temperature (the cooling or quench rate) after the point of sorbent injection. Tests are in progress to evaluate this effect over a range of quench rates between 100 and 1100°F/s (38–590°C/s), a range greater than that encountered in full-scale pulverized coal boilers. Preliminary results show that SO_2 removal may decline significantly at the highest quench rates, an effect that appears to depend on the sorbent used. This phenomenon, together with the dependence on injection temperature previously noted, highlights the need for an effective injection system design that can deliver the sorbent to the proper temperature regions within the furnace and achieve good mixing with the flue gas in full-scale applications.

Researchers have also evaluated the importance of sorbent particle size and initial surface area. They have examined a range of mean particle sizes from 0.75 to 35 μm in diameter by testing a wide array of manufactured and naturally occurring carbonate materials. Although higher sorbent utilization was observed with smaller particle sizes, the effect was small over the range of commercially practical pulverization, indicating that extraordinary attempts to optimize SO_2 removal by finer sorbent particle production would likely provide a limited return. Project personnel found no clear correlation between sorbent utilization and preinjection sorbent surface area, which suggests that this parameter cannot be directly used to indicate sorbent reactivity.

To better understand the processes that occur during calcination and sulfation reactions, researchers collected gas and solid samples for all sorbents from a pilot-scale furnace firing natural gas. The tests were conducted with natural gas to preclude any reactions with SO_2 and permit collection of sorbent and by-products without interference from fly ash. As a general rule, no significant differences have been observed in sorbent performance with coal or gas other than those attributable to temperature at the injection point. Properties of the sorbent injected into a gas-fired furnace, therefore, are expected to correspond to those with coal in the regions of interest away from the burner zone.

A major finding from these measurements has been the close correlation between calcium utilization and the surface area of the calcine sorbent (i.e., the surface area of the sorbent after calcination in the furnace). Sorbents and injection conditions that result in higher calcine surface area remove more SO_2. EPRI has initiated efforts to explore means of artificially enhancing reactivity by external pretreatment of the sorbent to increase initial surface area. One approach involves thermal pretreatment of sorbents prior to furnace injection. Preliminary bench-scale tests with pressure-hydrated lime have succeeded in producing sorbent surface area three times greater (up to 100 m^2/g) than the highest surface area measured in the furnace. However, preliminary injection tests are thus far inconclusive regarding enhanced SO_2 removal with externally generated high-surface-area sorbents. EPRI is also evaluating the use of chemical promotors to increase the rate of SO_2 absorption on the surface of the sorbent particles.

Although this work is directed specifically toward application in pulverized-coal-fired boilers, EPRI has begun a new cofunded project with Babcock & Wilcox Co., Baltimore Gas & Electric Co., and Atlantic Electric Co. to assess the applicability of furnace sorbent injection to cyclone boilers. This work will involve tests on a 6 × 10^6 Btu/h experimental furnace that has been equipped with a cyclone burner. Testing will demonstrate SO_2 removal with sorbents injected into the upper cavity of the main furnace (in a similar fashion to that envisioned for a pulverized-coal boiler), where high thermal quench rates up to 1500°F/s (800°C/s) may represent a worst case for application. Another objective is to evaluate the impact of the process on convective tube surfaces by measuring fouling buildup rates, deposit cleanability, and heat transfer on a simulated convective tube array. On the basis of the test results, researchers will assess the engineering feasibility of retrofitting the process to a full-scale cyclone boiler.

Power plant effects

Several process performance and plant operating issues must ultimately be resolved before widespread application of the technology can be confidently considered. The sorbent utilization and SO_2 removal achieved in the laboratory must be demonstrated at full scale. Assuming that the required residence times exist at favorable temperatures, scale-up should be primarily a matter of achieving proper sorbent distribution and mixing in a large volume. Furnace mixing and dispersion models developed in this project (RP2533) and in a related NO_x control project (RP2154) will establish design criteria for sorbent injectors that can eventually be applied at specific sites by using information on a given furnace's temperature profiles and flow patterns.

Sorbent injection affects power plant operation by increasing the mass of solids passing through the boiler and changing the physical and chemical properties of the ash. These changes can affect furnace conditions, including slagging, fouling, and erosion, and can affect the operation of downstream particulate control and waste-handling equipment. In each case these problems may be more difficult to manage in retrofits than in new units where they could be accounted for from the start.

Early laboratory tests conducted by Combustion Engineering, Inc., under RP899-2 and more-recent field trial experiences elsewhere have indicated that most cases of fouling, slagging, and erosion of heat transfer surfaces can be managed by conventional soot blowing, although increased numbers of blowers, careful placement, and modified operation may be required. The potential impacts and countermeasures are site specific, and full verification must await further operating experience at large scale.

To get a preliminary indication of the impacts on particulate control, researchers have measured fly ash size distribution and electrical properties in conjunction with pilot development testing under RP2533-1. Results indicate that ash resistivity can increase two to three orders of magnitude during sorbent injection and that the concentration of submicrometer particles may also increase, depending on the sorbent used. Deterioration in electrostatic precipitator (ESP) performance and increased particulate emissions can be expected unless steps are taken to counteract these effects. Initial attempts to restore electrical resistivity by flue gas SO_3 conditioning suggest this is an effective technique, but further work is required to identify optimal ESP improvement or conditioning systems for a given application.

Solid-waste disposal is another area where furnace sorbent injection could require modified power plant design or operation. Increased quantities of solid waste that includes potentially alkaline leachate, exothermic reactions of unreacted lime with water, and the possible cementitious behavior of the waste when wet highlight the need for a detailed assessment of ash transportation, storage, and disposal practice. An evaluation of whether some of these properties might be beneficial for ash utilization is also necessary. Such assessments will be performed in a new project in the Heat, Waste, and Water Management Program, which will consider the solid-waste management of furnace sorbent injection and other SO_2 control technologies that are emerging (RP2708).

Prototype evaluation

EPRI is currently working with government agencies, utility companies, and other interested groups to initiate prototype retrofit and test programs on several 50- to 150-MW coal-fired boilers. The major objectives of these prototype programs are to apply the results of process development projects described above to provide generic utility data on process design and performance and to resolve plant impact issues that cannot be fully addressed in the laboratory. Tests on units of this size are considered the next logical step in the development of the technology for commercial application.

EPRI participation in the prototypes and other complementary industry programs will be continued under a new research project that supports testing and engineering design (RP2786). The first prototype program is scheduled for Public Service Co. of Indiana, Inc.'s Wabash River generating station in Terre Haute, Indiana, on a 100-MW wall-fired boiler equipped with an ESP. This site is an ideal test location for this project; the unit is small enough to permit economical evaluation of a number of sorbents, coals, and ESP upgrades, but it is still typical of many boilers that would be candidates for retrofit SO_2 controls. In addition, the ESP is relatively small, which provides the opportunity to demonstrate the effectiveness of upgrade approaches in a very challenging and realistic environment. The major participants include Public Service (which will host the tests and provide overall management), the state of Indiana, coal companies, and EPRI. Other utility companies and interested groups, including sorbent suppliers and transportation companies, are also expected to participate.

EPRI will be responsible for technical direction and funding for process design, and it will also plan, manage, and fund all testing activities. The testing will include a two-month pre-retrofit baseline test, scheduled for completion late this year, and a one-and-a-half-year process optimization and long-term operational test, scheduled to begin in early 1987. The preliminary plan calls for testing on two coals and two or three sorbents; the tests will include evaluation of SO_2 removal efficiency, boiler impacts, low-cost ESP upgrades (humidification, flue gas SO_3 conditioning, and/or pulse energization), and alternative dry waste handling processes.

At the same time, EPRI is exploring participation in other furnace injection projects, where appropriate, to ensure that operational and other issues of concern to utilities can be fully addressed and that results from our development programs are available and incorporated. Two such projects are the 105-MW demonstration of the limestone injection multistage burner technology planned by EPA and Ohio Edison Co., and a 650-MW trial of furnace sorbent injection under consideration for the Homer City station jointly owned by Pennsylvania Electric Co. and New York State Electric & Gas Corp.

Process economics

The capital cost of retrofitting furnace sorbent injection to a coal-fired boiler has been estimated to be between $25/kW and $120/kW. The large range reflects the cost sensitivity to uncertainties associated with the unresolved commercialization issues. Levelized costs, estimated at between 5 and 12 mills/kWh, are influenced predominantly by coal sulfur content and calcium utilization (which determine the quantity of sorbent required), the costs of sorbent, and solid-waste disposal costs. The lower value of levelized cost is for burning 2% sulfur coal with minor effects on the power plant (easy retrofit). The higher value corresponds to a difficult retrofit on a furnace burning 4% sulfur coal.

Substantially lower process costs would be possible if improved sorbent utilization could be achieved at reasonable sorbent costs. Not only would sorbent consumption be less for an equivalent level of SO_2 removal, but smaller material handling requirements and lower solids loading in the boiler and downstream equipment would reduce the plant impacts and their associated costs. For this reason, the current project emphasizes development of higher-reactivity sorbents.

EPRI has recently initiated a new project with Stearns-Catalytic Corp. to update the economic assessment and incorporate results from the latest process development activities (RP2533-4). Additional cost estimates for advanced dry injection emission control systems, which combine furnace sorbent injection and other postfurnace dry injection technologies, are also planned. *Project Managers: Michael McElroy and George Offen*

R&D Status Report
ELECTRICAL SYSTEMS DIVISION

John J. Dougherty, Vice President

DISTRIBUTION

New wood preservatives

In 1979 EPRI initiated a project with the Institute of Wood Research at Michigan Technological University to develop improved materials and processes for treating new poles (RP1528). The major goal of this project was to improve the control of wood decay in utility poles and to extend the control over a longer time.

This project, which is nearing completion, has resulted in two major accomplishments.

- Introduced two preservative systems: alkyl ammonium compounds for wood not in contact with the ground and ammoniacal copper fatty acid for in-ground use

- Established the value of a fungi cellar as a means to evaluate the effectiveness of preservatives more rapidly than by field stake tests

The preservatives introduced may soon be available for utility use; they have been presented to the American Wood Preservers Association (AWPA). Utilities will find these preservatives offer many benefits. Both are just as effective as currently available treatments, and because neither contains materials toxic to mammals, they are much more acceptable environmentally. In addition, these preservatives are cost competitive with available preservatives.

Utilities will find the ammoniacal copper fatty acid of particular interest for treating poles because it yields a pole that resembles a chromated copper arsenate (CCA) treated pole in color but contains no toxic arsenicals. In addition, the pole will be easier to climb than CCA-treated poles because of the addition of the fatty acid, which softens the wood.

The value of a fungi cellar (a humid, warm environment for fungi growth) is that it has the same effect on the preservative in one year as that observed in three years of exposure in standard field stake tests. Tests conducted in the cellar are much less costly than those in a field stake test, and utilities can obtain earlier screenings of new preservatives that they plan to use on wood products.

This project is scheduled for completion in late 1985, and the final report is expected in early 1986. *Project Manager: Harry Ng*

Electrical interference on power lines

Distribution and transmission lines are designed to conduct electric power at 60 Hz. These lines also conduct and radiate harmonics and other electrical noise generated by both utility and customer equipment. Such harmonics and noise are potential sources of interference with digital communications and control systems. Typical victims of interference are transmission and distribution line carrier systems, control and switching equipment, and substation SCADA (supervisory control and data acquisition) equipment. In addition, this radiation is an interference to radio and television receivers, military radar, railroad control systems, communication receivers, and ship and airborne navigational systems.

A project funded by EPRI and now completed provided new baseline data on electrical interference to both utilities and manufacturers (RP2017). Using the results of this project as guidelines, manufacturers can now design electrical and electronic equipment to minimize its susceptibility to harmonics and noise.

During this project, harmonics and electrical noise measured on utility distribution systems were analyzed, producing amplitudinal, spectral, and temporal characteristics of both voltage and current. Conducted and radiated noise associated with more than 100 distribution feeders at 11 utilities located throughout the United States were examined. Noise and harmonics that could interfere with distribution line carrier (DLC) systems were measured at frequencies from 1 to 15 kHz, and additional noise measurements were made over the frequency range of 10 Hz to 1 GHz.

Electrical characteristics of the sources of noise change with the frequency range investigated. The noise was divided into distinct types. The temporal and spectral characteristics of each type of noise were determined, and sources for each type of noise were identified and located whenever possible. Measurement techniques and equipment were described, new instrumentation and techniques having been developed because standard equipment and practices were inadequate for these measurements.

The effects of radio noise were remarkably similar on distribution lines at all utilities visited; no significant differences could be attributed to location (north, south, east, or west), terrain (mountainous or smooth), or population (urban, suburban, or rural). The primary type of noise affecting the performance of DLC systems was discrete harmonics of the 60-Hz frequency. The sources of these harmonics were always switching devices and nonlinear—usually customer—loads. No case of utility-generated harmonics was identified as a limiting factor in harmonics on distribution lines at DLC frequencies.

Significant temporal changes were found in amplitudes of noise and harmonics at and near DLC frequencies. These changes were usually abrupt rather than gradual. Many such changes were associated with customers who switched loads on and off or altered loads by load control devices.

Gap noise was found on distribution lines at all utilities. Gap noise can be a significant source of interference to many communication and radio services that use frequencies from 30 kHz to 500 MHz. Gap noise, however, is not a source of noise or interference on DLC systems that operate at frequencies below 30 kHz.

Experimental DLC systems from three major suppliers were observed in operation during the measurements. All systems propagated two-way signals along distribution lines and were limited in performance by harmonics of the power frequencies within the band paths of the DLC receivers. Also, signals from a DLC system operating on a distribution line were observed on other distribution lines operating out of the same substation and on distribution lines operating from other substations. In cases in which signals were found on lines from other substations, a transmission line coupled the substations and was the likely path for DLC signals.

A significant number of communications systems used utility distribution lines to propagate signals from one location to another. Their operating frequencies were within the range used by DLC systems (1–15 kHz). Although no case of direct interference was found between a utility DLC system and a customer-operated system using the same frequency, any significant expansion of DLC systems by the utilities would eventually result in interference among users.

Resonant peaks in harmonic amplitudes were noted at and around DLC frequencies. These peaks changed in amplitude and sometimes in frequency as loads on the line were changed.

The data and results published in the final report will be available to several sectors of the electric utility industry. On the basis of this report, the utilities can consider mitigation techniques, including filtering and shielding, to minimize interference. Manufacturers of high-power switching equipment can see characteristics of the harmonics that their equipment generates, and manufacturers of low-power electronic equipment can see characteristics of harmonics that may interfere with their relatively sensitive equipment. Standards committees can also use these results as guidelines for developing new standards to protect both a utility and its customers. *Project Manager: William E. Blair*

Wood pole decay

Controlling the decay of wood poles already in service is of considerable interest to utilities. Utilities can save money by deferring replacement of poles whose life can be extended. An earlier project demonstrated that the use of a fumigant can extend the life of Douglas fir and western red cedar poles by as much as 10 years (RP212). To determine the effectiveness of fumigants on southern yellow pine poles, EPRI initiated a project with the College of Environmental Sciences and Forestry at State University of New York at Syracuse (RP1471).

At the start of the project in 1980, poles ranging in age from 10 years to 40 years that had been treated with penta or creosote were assayed to identify the total fungal population. They were then treated with either Vapam or chloropicrin fumigant. Each year after this fumigant treatment, core samples of the poles were removed and analyzed for reinvasion of fungi.

The data obtained to date show that in the five years since treatment, the southern yellow pine poles treated with Vapam have started to show an increase in the number of fungi reinvasions; in the first two years, no reinvasion was detected. Those poles treated with chloropicrin have shown only minimal reinvasion of fungi four years after treatment, with no reinvasion detected in the first two years.

This project continues for another three years to gather more data on the fungi reinvasion and to determine the point at which another application of fumigant may be necessary.

The results of this project for the first three years were published in December 1982 (EL-2768), providing data on two years of fumigant effectiveness. *Project Manager: Harry Ng*

UNDERGROUND TRANSMISSION

Dynamic rating and underground management system (DRUMS)

The last five years have seen rapid developments in microelectronics and digital signal processors for many industries and applications. A few successful demonstrations of systems to monitor the thermal ratings of underground transmission circuits, such as those by Public Service Electric & Gas (funded by DOE), and separate initiatives by Florida Power & Light have encouraged further interest in microtechnologies.

After an in-depth assessment of these efforts produced favorable recommendations in 1983, EPRI funded an important introductory study by Underground Systems, Inc. (RP7898-3). Recommendations had been made on 12 specific applications for sensing, monitoring, and analyzing various underground transmission functions. Various ideas for receiving and communicating the data for control and operating purposes were also addressed.

Received in January 1985, a summary report of the intensive one-year investigation and analysis fully supported the practicality of the various applications and the likely benefits for utility underground transmission. As in the initial recommendations prompting the study, 12 applications were found to be attractive, beneficial, and feasible.

- Monitor dynamic temperatures and thermal ratings
- Determine dynamic, short-time emergency ratings
- Predict temperature profiles for HPOF cables under future loading criteria
- Monitor thermal backfill stability
- Compare thermal stability of joints
- Monitor insulation aging and remaining useful cable life
- Rapidly detect and locate faults
- Detect and locate leaks accurately and promptly
- Monitor pothead pressure and gas content
- Locate joints in casings
- Determine cable thermomechanical bending
- Survey anticorrosion pipe coating

Implementation of the 12 applications would be enhanced by low-cost, dependable communication systems for the receipt of data and return of commands. A fully monitored, complex dynamic rating and underground management system (DRUMS) would require the installation of monitors in every manhole, which would be capable of analyzing and transmitting data to central control.

The central premise of DRUMS is to tie together present-day technology in the areas of cable rating, leak location, fault location, dielectric aging, corrosion protection, thermomechanical bending, and transient event recording. The communications bus can be the containment pipe system or the hydraulic fluid therein or the cable shields—all are feasible, reliable, and economical means to communicate the data, intelligence, and commands.

The substantial benefits of microtechnology to underground transmission have already been demonstrated in a few operating systems. The advantages of DRUMS are the simplicity of retrofit, the ready adaptability to existing systems, and the effectiveness of implementing all 12 or more applications for the operation and increased dynamic ratings of underground transmission. *Project Manager: Stephen Kozak*

OVERHEAD TRANSMISSION

Improved foundation design computer program

In 1978 EPRI initiated a contract with GAI Consultants, Inc., on laterally loaded drilled piers (RP1280-1). The objective was to improve the method of designing drilled pier foundations that are subject to high overturning moment loads. This foundation, widely used for transmission structures, consists of a reinforced concrete cage placed in an augered hole that is then filled with concrete. Because the conventional methods indicated consistently conservative design, it was suspected that utilities were spending too much money on foundations.

This project was a success. The most significant result was the computer program PADLL (pier analysis and design for lateral loads). PADLL has become EPRI's most extensively distributed software product: there are over 100 licensees for this code; EPRI surveys indicate that PADLL is widely used; and the project results were well received at four seminars held for technology transfer. In addition, the project results have saved utilities money. An earlier R&D status report (*EPRI Journal*, September 1981) reported that Jersey Central Power & Light had estimated a $1 million saving on a construction project. Recently, Philadelphia Electric Co. used PADLL on a construction project and estimates saving over $1 million on the foundations for its Limerick 230-kV transmission lines.

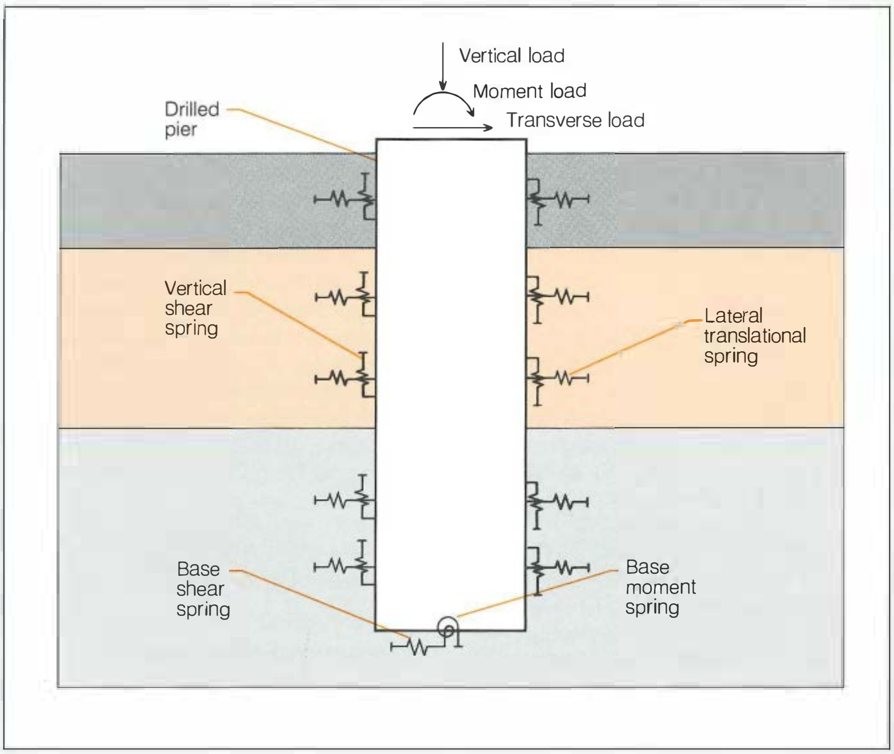
The semiempirical model used in PADLL represents the subsurface environment of a pier. Each of four springs represents a different soil response (Figure 1). This representation of the pier is not too far removed from the direct embedment foundation. But instead of placing a reinforced concrete pier in an augered hole, the direct embedment method places the transmission pole in the hole and then backfills the remaining annulus. Figure 2 shows how direct embedment might be modeled in the context of the PADLL model.

Direct embedment construction is common for wood poles. Its use in constructing transmission lines with steel or concrete poles could significantly reduce foundation costs. As in so many geotechnical areas, however, there are no hard data to support the many design methods that might be proposed. "Ten percent of pole length plus two feet" is the rule of thumb for determining the direct embedment setting depth of wood poles. Although this is no doubt a successful criterion for wood, other, higher-strength, pole materials carry loads that stress soils to a much greater extent than is allowed by wood poles.

A group of utilities were convinced that research on direct embedment was important and approached EPRI with a cofunding proposal. An agreement between EPRI and each utility to share the cost equally allowed the research to begin immediately. Seven utilities are cofunding this work.

Pennsylvania Power & Light Co.
Jersey Central Power & Light Co.

Figure 1 This four-spring subgrade modulus model is the PADLL representation of the soil response to forces caused by the loads on a drilled pier foundation.



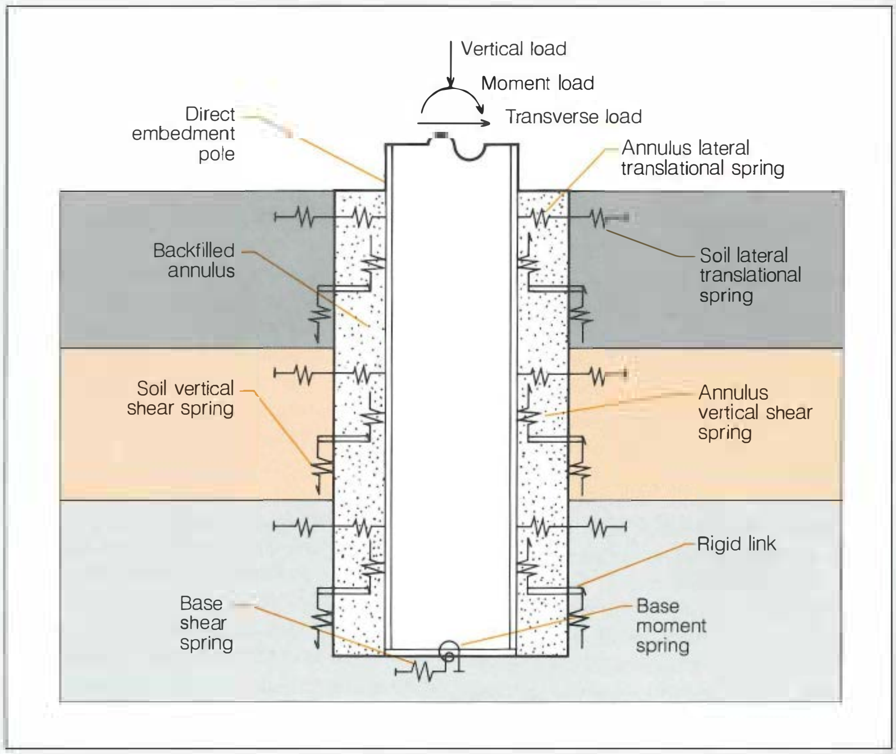


Figure 2 This four-spring subgrade modulus model is the MFAD representation of the combined annulus and soil response to forces caused by the loads on a direct embedment pole foundation.

Delmarva Power and Light Co.
Virginia Power Co.
New York State Electric & Gas Corp.
Kansas Gas and Electric Co.
Potomac Electric Power Co.

The design model used in PADLL has been modified to include representation of the annulus material, and a series of field tests at the cofunding utilities is under way. The resultant model for direct embedment foundation design will be available in early 1986. The computer program with this design option, MFAD (moment foundation analysis and design), will incorporate the PADLL model for design of piers. The new name is a more apt expression of the foundation design and analysis loading mode, which is not restricted to piers.

Another computer program for the design of transmission line foundations will also be released early in 1986. This program, CUFAD (compression/uplift foundation analysis and design), is based on work done at Cornell University (RP1493) and will be an implementation of the unified model proposed for design of foundations subject to axial loads in *Transmission Line Structure Foundations for Uplift-Compression Loading* (EPRI EL-2870) and further refined in the recently published *Critical Evaluation of Design Methods for Foundations Under Axial Uplift and Compression Loading* (EPRI EL-3771). *Project Manager: Vito Longo*

POWER SYSTEM PLANNING AND OPERATIONS

Load management

The number of load management installations has grown rapidly over the past five years. Many of these installations were justified by using an analysis of load research data, generating costs, bulk power purchase expenses, and projected future costs. To be useful in regular system operations, however, the capabilities for managing loads must be translated into daily operating strategies.

Most of the earlier load management installations in the United States have been implemented by electric cooperatives; their installations were easily justified, and their operating strategies are relatively simple. But for utilities that own and dispatch their own generation, the problem of implementing load management in daily operations becomes much more involved. Specifically, when the penetration of a utility's load management reaches a certain level, the utility must coordinate day-to-day load management actions with the overall system dispatching functions to maximize the benefits of load management. This requires methods to determine how to use load management in dispatch control centers in the most economic way while maintaining power system security.

Started in September 1983, this project (RP2202) is a 27-month study by Energy and Control Consultants, Inc., with Florida Power & Light Co. (FP&L) as the host utility. Its overall objective is similar to that of RP2336 on dispersed storage and generation devices for normal system operations.

- Develop a set of practical computer programs for the effective use of load management in normal daily operations
- Demonstrate the practicality of these techniques by testing a prototype program on the backup control computer in the FP&L dispatch control center, using data from its power system
- Participate in a coordinated plan to develop a practical, advanced-generation control program that will incorporate load management (RP2202) and dispersed storage and generation devices (RP2336) into daily operations

To date, limited surveys have been made of electric utilities and load management equipment vendors to identify current practices and future plans for load management. The primary factors influencing the integration of load management into control centers are the operational objectives, the time frame of use, the constraints on use, and the penetration level. Currently, a computer program is being developed for daily use by system operators to analyze the load management options. In addition, the effect of this program on other applications programs, such as unit commitment and economic dispatch, is being investigated. Two seminars on the results of this project are planned: one for early December 1985 and one for mid January 1986. *Project Manager: Charles J. Frank*

Dispersed storage and generation

The term *dispersed storage and generation* (DSG) identifies a group of power sources that includes cogeneration, small hydroelectric, wind turbine, storage battery, solar thermal electric, and photovoltaic devices. Over the past several years, an increasing number of DSG devices have been installed by electric utilities, and more installations are expected in the future. These installations vary in ownership, type, size, and number at a specific site. The amount of available DSG power can have an effect on such daily operations as operating reserve and generator load-following requirements.

Started in December 1983, this project (RP2336) is a 27-month study by System Control, Inc., with San Diego Gas & Electric Co. as the host utility. The objectives are similar to those of RP2202 on load management for normal system operations, discussed above.

To date, limited surveys of electric utilities and DSG vendors have been completed. The primary factors influencing DSG device integration into control centers are the penetration levels, controllability, dispersion, ownership, and types of the DSG devices. A computer program is being developed for daily use by system operators to analyze the DSG options. A seminar on the results of this project is planned for March 1986. *Project Manager: Charles J. Frank*

Harmonics analysis software

Since early 1984 EPRI has been distributing a computer program (HARMFLO, version 1.0) that simulates the creation and propagation of harmonics in balanced, three-phase transmission and distribution networks. In that time, more than 30 utilities and industrial firms have used HARMFLO for the analysis of harmonics sources and possible remedies.

In the third quarter of 1985, a new version (HARMFLO, 3.1) will be available from the EPRI Electric Power Software Center. The new version, produced by Purdue University and Minnesota Power & Light Co. (RP2444-1), differs from version 1.0 in its modeling capabilities: 12 pulse converters, HVDC controls, and zero-sequence models have been added. Hence, both greater efficiency and 100-bus studies are now possible.

Field tests were conducted to compare HARMFLO predictions with recorded harmonics at an HVDC terminal and in the surrounding area. The simulation results were within 10% of the recorded values for frequencies below the eleventh harmonic (660 Hz). This comparison is satisfactory, considering the crudeness of the models used in HARMFLO. Load modeling at higher frequencies had a particularly profound effect on the results.

HARMFLO results also matched those of the electromagnetic transients program (EMTP) simulations, which used the same transmission system model. This comparison shows that HARMFLO can replace the much more sophisticated but difficult-to-use EMTP for balanced system conditions.

Continuing R&D is directed at making HARMFLO easier to use and increasing the number of load modeling options available to the user. A new version containing these improvements (version 4.0) is expected to be released in the second quarter of 1986. More field tests are further validating the program. A newsletter for current HARMFLO users and a seminar for new users are planned for 1986. The contractor, Purdue University, is also prepared to answer questions about program use. *Project Manager: James V. Mitsche*

R&D Status Report
ENERGY ANALYSIS AND ENVIRONMENT DIVISION

René Malès, Vice President

MASSIVE AEROMETRIC TRACER EXPERIMENT (MATEX)

Because its fossil fuel power plants emit large quantities of sulfur and nitrogen oxides, the U.S. electric power industry is a focal point for emission control strategies designed to contain or reduce acid deposition. The possible cost of emission reductions is very large—on the order of billions to tens of billions of dollars per year—and thus it is in everyone's best interests to know in advance whether a proposed emission control strategy will produce commensurate environmental improvements. Unfortunately, the current state of knowledge regarding the transport of precursor materials from multiple sources, their chemical transformation to acidic forms, and the regional deposition of both wet and dry materials cannot satisfy this assessment requirement. In its continuing work to fill the knowledge gap, EPRI has identified the stumbling blocks in a major tracer gas study designed to characterize pollutant transport, transformation, and deposition.

There is a recognized need for better understanding of both the effects of acid deposition and the effects of specific emission control plans on that deposition. In response to this need, the federal government initiated the National Acid Precipitation Assessment Program (NAPAP) to assess damage that might be caused by acid deposition and to develop a better understanding of the source-receptor relationship so that the efficacy of emission control strategies can be judged. The research plan specifies that the acid deposition problem be dissected into its component parts—source, transport, transformation, and deposition—and that rigorous scientific analysis and development be performed in each component area. These research results are then to be developed into a comprehensive regional acid deposition model, constructed under NAPAP auspices at the National Center for Atmospheric Research (NCAR). In keeping with the congressional mandate for NAPAP, the improved assessment tools should be available for use in 1988 or 1989. This schedule clearly calls for research that would normally occupy a decade or more to be compressed into three or four years; such compression requires a level of success in key areas of research that simply cannot be guaranteed.

The MATEX concept

Recognizing that the federal research may bring only marginal improvement in the assessment tools needed to establish source-receptor relationships, EPRI suggested a parallel and complementary attack on the problem: intensive and extensive field measurements of the key atmospheric transport, chemical transformation, and wet and dry deposition variables over the eastern North American continent. It was believed that the possibilities for success of such a brute force approach would be enhanced by the emergence of an inert gaseous tracer technology that can uniquely identify air parcel motions over distances greater than 1000 km (600 mi). This tracer capability would permit evaluation of (1) the frequency with which air moved from a given source area to a given receptor area, and (2) the path it followed during each trip, including other source areas over which it passed en route.

Tracking air mass motions in this way could also permit the direct measurement of wet and dry deposition of emitted pollutants and their products along the air mass trajectory and in the selected receptor areas. These empirical analyses could conceivably provide answers to the question of the relative contributions of distant and nearby sources to observed acid deposition. In addition, the measurement of emissions, meteorologic variables, chemical species concentrations, and observed deposition would provide the information necessary to validate and improve regional acid deposition models on both a modular and a holistic basis.

This concept, quickly dubbed MATEX, was brought to the attention of the joint chairs responsible for the operation of NAPAP. For its part EPRI pledged a contribution of $20 million, subject to the results of a comprehensive feasibility analysis and the pledging of the balance of the costs (then estimated to be about $100 million) by other agencies. The NAPAP joint chairs agreed that pursuing this alternative was preferable to sole reliance on modular scientific research and model synthesis and asked for a comprehensive feasibility analysis of the MATEX concept.

Two such analyses were initiated in 1983 and completed in 1984: EPRI funded an evaluation of the full-scale MATEX concept, and EPA funded an analysis of a geographically less ambitious concept known as COMPEX (comprehensive experiment). At a joint workshop held in September 1984, the MATEX and COMPEX evaluation teams compared findings and derived recommendations for future empirically oriented research on source-receptor relationships in acid deposition phenomena.

Feasibility findings

After an exhaustive analysis of the scientific and logistic feasibility of the MATEX concept (RP2434-2), the MATEX team concluded that the basic concept was sound and that eventually such an experiment could produce the required information for empirical assessment of source-receptor relationships. However, the MATEX and COMPEX study teams found the probability of success for the experiment to be undesirably low because of certain major technical constraints.

- Current methods for measuring dry deposition of chemically reactive gases and particulates are inadequate and may lead to cumulative errors (bias), as well as uncertainty, when used to calculate the integral loss of pollutants over long travel distances.

- Cumulative errors in both wet and dry deposition estimates cause the uncertainty of mass balance calculations for reactive pollutants to grow considerably (>100%) after only one day of travel if only inert tracers are used; in contrast, the goal is to achieve uncertainties of less than 50% for travel times of three or four days.

- Inert tracers alone are inadequate for estimating multiple-source contributions to wet deposition, primarily because of differences in the way clouds process inert and chemically reactive materials.

The study teams concluded that the logistics of the experiment and the data analyses, while formidable, could be managed. However, on the basis of several experimental scenarios, using tagged chemically reactive materials as well as inert gaseous tracers, the costs for a full-scale MATEX program were estimated to be between $150 million and $285 million. Reflecting these findings, the primary recommendation of the study team was that MATEX be deferred until successful methods for reducing the uncertainty of the loss terms become available—for example, through the development of tagged chemically reactive tracers that mimic the chemistry of sulfur and nitrogen oxides. Such a tracer capability, available on a large scale and for multiple releases from a variety of source areas, would also ease the dry deposition measurement problem because the deposited tracer could be measured directly.

The clear need for further tracer technology development to ensure the success of MATEX places this approach outside the NAPAP requirement for producing definitive results by 1988–1989. Although the completion of more limited measurements is conceivable, these results would be more appropriate for model development and evaluation than for drawing definitive empirical conclusions. Unless compelling reasons arise to defer the NAPAP assessment schedule for several years, a full-scale MATEX program and the associated tracer technology development are justified only on the grounds that similar needs for comprehensive description and understanding of the regional air quality system will exist in the future. In the meantime, the need to provide the best possible information for the NAPAP assessment still stands.

Shifting focus

With MATEX in abeyance, EPRI's research activities and planning have focused on ensuring, to the extent possible, the scientific credibility of the regional air quality models and data bases to be used in the NAPAP assessment. Research on cloud chemistry (RP2023) has been extended and diversified to clarify the expected chemical pathways and reaction rates for preprocessing of sulfur dioxide and nitrogen oxides and the subsequent wet and dry deposition of acidic materials. EPRI is providing supplemental funding to the regional model development efforts at NCAR and at Environmental Research & Technology (the latter under the Ontario Ministry of Environment and the Federal Republic of Germany) to help ensure the reliability and timeliness of those efforts (RP1630-21). In addition, EPRI is moving to fill the data gap for real-world measurements of total deposition, data necessary for rigorously evaluating the reliability of model predictions. The cost of these research activities promises to be substantial—several tens of millions of dollars over the next four or five years—but this must be weighed against the considerable value of producing better answers. *Project Managers: Robert M. Patterson and Glenn R. Hilst*

CHRONOLOGICAL SIMULATION OF GENERATING SYSTEM OPERATION

With some recently developed software, operators and planners can simulate chronologically the hourly commitment and dispatch of a power supply system. This allows them to determine if the system is physically capable of supplying the expected load and to estimate the cost of production. Dispatch simulation based on load duration curves is simpler and quicker than chronological simulation; however, these curves do not capture the full effects of commitment decisions and technological constraints—for example, the limited reservoir capacity of pumped-storage plants and the ramp rate limitations of baseload thermal units. If such constraints are overlooked, the role of peaking units, storage units, or dispatcher-controlled load management may be estimated incorrectly. The effects of commitment decisions and technological constraints can now be analyzed more precisely with a new computer program called BENCHMARK (RP1808), which EPRI plans to release this year. As its name signifies, the program is intended to calibrate, or benchmark, short-cut calculations based on load duration curves. It will be featured at a conference on production simulation in Chattanooga, Tennessee, October 22–24, 1985, cosponsored by EPRI, the Tennessee Valley Authority, and the University of Tennessee at Chattanooga.

In planning and operating electric generating systems, situations can arise where it is necessary to simulate hourly generation—both commitment, which refers to the timing of unit startup and shutdown, and dispatch, which refers to the apportionment of load among the operating units. Such an analysis simulates the duties faced around the clock by power system operators. A difference, however, is that the operator has before him information on the current status of his system, whereas the analyst is looking at a point in the future and must postulate the whole range of conditions that may occur.

Dispatch techniques have evolved along with multigenerator power supply systems, which appeared at the turn of the century. An initial approach was average-cost loading, which, strictly speaking, involves starting up and loading one unit at a time. The units are selected according to their cost per kilowatt-hour at full output. This type of dispatch does not depend on the chronological sequence of hourly loads. It can readily be represented or simulated by using a load duration curve, which is formed by sorting the loads by magnitude. The area under the curve can then be divided into horizontal bands corresponding to the output of individual units, with the baseload units in the lower bands, the intermediate units further up, and the peaking units in the uppermost bands.

In the 1920s dispatch techniques based on marginal cost were introduced. In this approach increments of power are apportioned to all the units in operation, with output adjusted so that all units operate at the same marginal cost. This type of dispatch cannot be represented exactly with a load duration curve.

Another issue that arose was how to represent the effects of forced outages. Data became available that statistically defined a forced-outage rate. This led to the use of pseudo deratings in load duration curves; for example, a 100-MW unit with a 10% forced-outage rate was represented as a 90-MW unit. Although this practice gives the correct energy output, it does not give either the correct number of operating hours or the correct power output. Such load duration curves, therefore, cannot assess the adequacy of a supply system.

This problem was overcome in the 1960s through the concept of the equivalent load duration curve. The time axis was replaced by a probability axis and the power output axis was replaced by an axis showing the sum of the output and the amount of capacity expected to be on forced outage. The axes were interchanged to show probability as the dependent variable. It then became possible to define loss-of-load probability in terms of the amount by which load and outages together exceed the installed capacity. Thus the equivalent load duration curve was able to replace various rules of thumb for specifying required reserve margins.

Still another difficulty was encountered in representing the dispatch of pumped-storage hydroelectric plants. The basic problem with using a load duration curve in this situation is that the hourly sequence is lost, and only information on load magnitude remains. To the degree that load magnitude is correlated with time of occurrence, a simple economic rule can be assumed: pump at low load levels, which probably occur at night, and generate at high loads, which probably occur during the day. Nighttime pumping would be followed by daytime generating, and a reservoir of limited capacity would suffice.

This simple picture may break down for several reasons. The load duration curve could cover a period of many days—even a year. The peak loads of the duration curve would refer to the highest loads for the entire period, and the analysis could miss the daytime pumping for days when the peak load was somewhat lower than the period peak. Other roles of a pumped-storage plant that take advantage of its quick response time would also be overlooked in such a simplified analysis. Load duration curve dispatch of pumped-storage plants is therefore inherently crude in comparison with the analysis that is possible with a chronological simulation.

An example of chronological dispatch simulation is presented in Figure 1, which shows an hourly load curve for a seven-day (168-hour) period. The generating units are grouped by fuel type and are stacked according to their degree of utilization. The system includes a pumped-storage plant; in this example the reservoir is specified to be one-third full at the beginning and end of the period. As shown in the figure, a chronological simulation of pumped-storage dispatch can track reservoir level and ensure that the reservoir is refilled when necessary. Because of this realism, such simulations are useful in assessing the degree to which pumped-storage plants eliminate supply shortages and reduce operating costs.

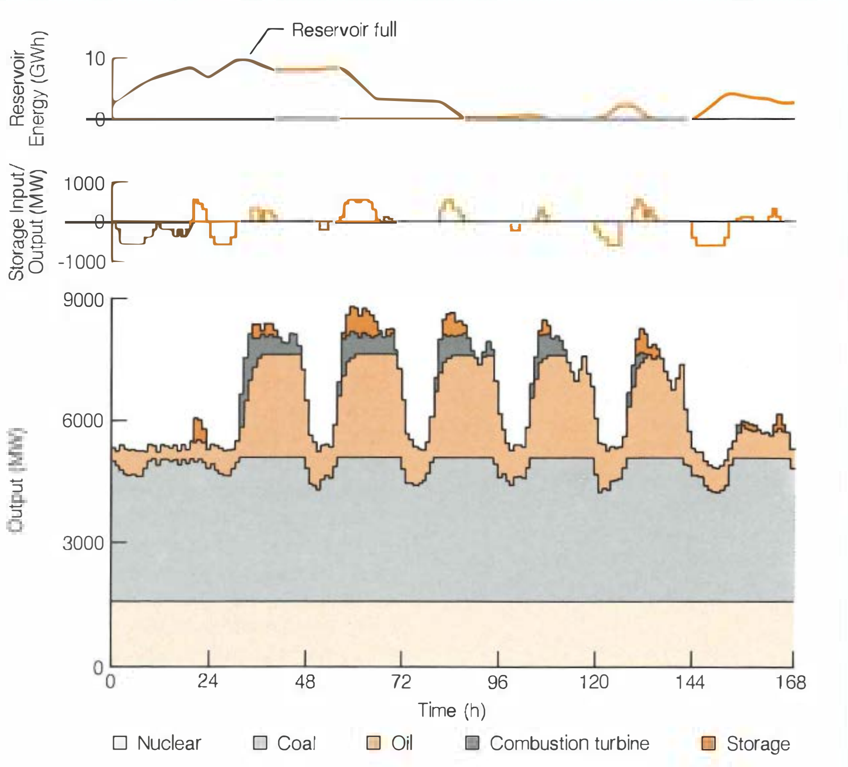


Figure 1 This BENCHMARK simulation of power system operation for a seven-day period shows the hourly utilization of five types of generating units, including a pumped-storage plant. The load profile in the main graph includes the energy required for storage plant pumping. The top graph tracks the water level of the pumped-storage reservoir, which is represented as the potential energy available from the reservoir. The middle graph tracks the power input and output of the storage plant; pumping is indicated by the negative values and generation by the positive values.

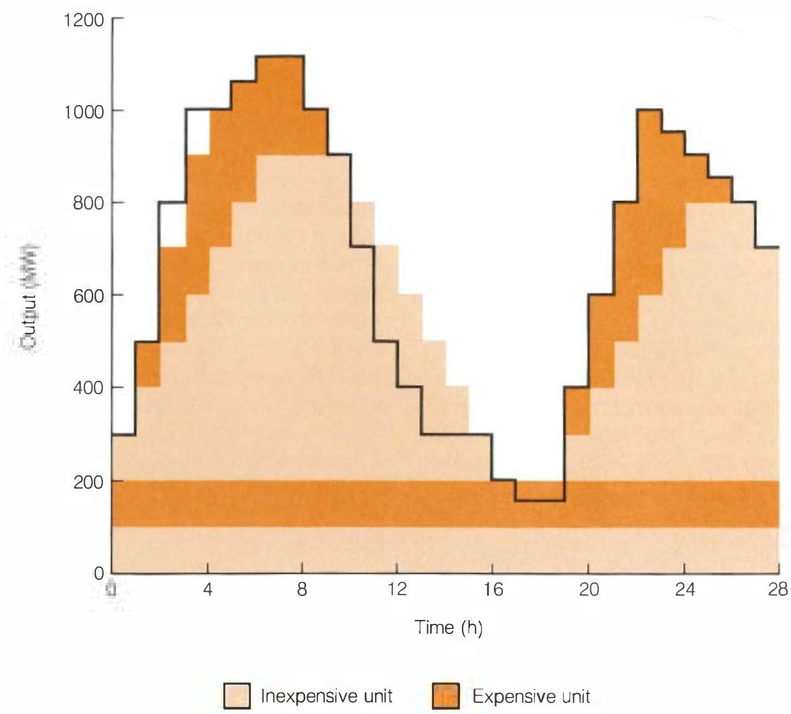
The system illustrated in Figure 1 includes coal-fired baseload units that cycle to some degree. This is necessary so that other units can be operated throughout the night—thereby avoiding the wear and cost associated with daily shutdown and startup.

In some cases it is important to simulate the ramp rate limitations of nuclear and coal-fired baseload units that were designed for full-load operation but are now called on to follow load. Their operating inflexibility can lead, for example, to what may be called "load shortages"—that is, situations when the load drops off faster than the output of these units can be decreased. Also, given ramp rate limitations, economic dispatch may call for increasing the output of some units while the total load is decreasing; this cannot be represented by dispatching units at equal marginal cost. Further, to avoid ramp rate problems, an operator may have to unload efficient units before load decreases rather than dispatch each hour at minimum operating cost.

These ramp rate situations are illustrated in Figure 2. In hours 3 and 4 there are capacity shortages, and either load would be shed or there would be an inadvertent inflow of power over the tie lines. In hours 11 to 15, load shortages occur because of the inability of the units to ramp down quickly enough. This could result in inadvertent outflows on the tie lines. In hours 18 and 19, the load drops below the minimum permissible output of the units, and there may be another inadvertent outflow. Hours 24 and 25 show the output of the inexpensive unit increasing while the total load is dropping off. If the operator had looked ahead to hours 11 to 15, the load shortage could have been avoided simply by ramping down the inexpensive unit several hours earlier. This requires a look-ahead feature in the simulation. The load shortage in hours 18 and 19 is due to the minimum operating limits of the generators, however, and could not be avoided without shutting down a unit.

Even if hourly loads could be forecast precisely, the future performance of a system would not be known with certainty because of the possibility of forced outages. In a supply system of 100 or more units, each subject to full or partial outages, there are a large number of potential combinations of available capacity. An efficient method of simulation that still permits the construction of hourly detail is to use random draws, or trials, in a Monte Carlo approach. Each draw specifies a set of available generating units; those units with high forced-outage rates are the ones most likely to be absent from the set. Once the set of available units is specified, the BENCHMARK computer

Figure 2 In this simulation of various ramp rate effects, load demand is indicated by the heavy black line and unit output by the shaded areas. Each unit has a minimum output of 100 MW. Unit operating limits can lead to mismatches between load demand and feasible generating output—as in hours 3 and 4, when load exceeds feasible output, and in hours 11 and 15 and 18 and 19, when minimum feasible output exceeds load.



program can calculate the cost or performance factor under consideration.

The computing effort is proportional to the number of trials and could be expensive. In practice, however, this need not be the case. The number of trials required varies with the square of the accuracy desired. In calculating an expected value for production cost, for example, if an accuracy goal of 1% requires 100 draws, a goal of 5% would require only four draws—that is, the number of trials would drop by a factor of 25. In a production cost simulation using a Monte Carlo approach, the distribution of outcomes will be skewed, with occasional outcomes considerably above the mean but without similar offsetting values below the mean. The high excursions in production cost are for the infrequent cases in which a substantial number of the most efficient units are simultaneously forced out of service.

In summary, attention to the chronological, or time-linked, behavior of a power supply system becomes imperative when the role of storage units is considered, when ramp rate limitations affect system response, or when other dispatch considerations (e.g., minimum uptime or minimum downtime) are brought into play. Because dispatch simulations based on load duration curves suppress chronology, they cannot strictly represent commitment decisions and will produce biased results. Ramp rate limitations may require peaking units, such as combustion turbines or pumped-storage units, to be operated whenever baseload units cannot respond rapidly enough to sudden increases in load. If ramp rate limitations are overlooked, the utilization of peaking units or the advantages of dispatcher-controlled load management may be underestimated. The actual operation of storage units requires tracking the amount of stored energy available—for example, the water level in a pumped-storage plant. This is readily accomplished in a chronological simulation but not in the load duration domain. If this limitation is not considered, the usefulness of storage plants may easily be overestimated.

Chronological simulation has a role, therefore, in analyzing both the physical and the economic behavior of electric power supply. It has been implemented in the BENCHMARK computer program, developed by EPRI jointly with several utilities and universities. BENCHMARK simulations will be helpful in addressing a variety of issues, including new-plant assessment, utility power transactions, fuel interruptions, maintenance rescheduling, and ratemaking. Still, its initial purpose—to calibrate load duration curves—may ultimately prove to be its most useful application. *Project Manager: J. K. Delson*

R&D Status Report
ENERGY MANAGEMENT AND UTILIZATION DIVISION

Fritz Kalhammer, Vice President

ADJUSTABLE-SPEED DRIVES

Motors keep American industry moving. They turn fans and blowers, run pumps and compressors, spin blenders and centrifuges, propel conveyors and process lines, twirl screws and augers. Many utility and industrial motors operate at only one speed or a few speeds. If they could be made to operate at limitless different speeds, each geared to the job at hand, they could save energy, improve productivity, prolong equipment life, and even enhance product quality. This range of speeds is now available to anyone who installs an electronic adjustable-speed drive (ASD).

Utility ASD retrofits

In 1982 EPRI contracted with Bechtel Power Corp. to evaluate a number of gas-, oil-, and coal-fired power plants to determine the economics of converting major auxiliary motors from constant speed to adjustable speed, using equipment available commercially worldwide (RP1464-03). With excellent cooperation from utilities and equipment manufacturers in providing data for the study, Bechtel was able to evaluate 200 motors in 60 utility generating units.

Bechtel enhanced an EPRI-developed screening technique that determines the energy savings obtainable by operating inlet vanes or control valves in the fully open position and adjusting flow rates by changing motor speed. Figure 1 shows the technical and economic data required to estimate efficiency improvement and payback. In determining the economics of power plant retrofits, Bechtel used equipment costs provided by a number of manufacturers in the United States, western Europe, and Japan. Bechtel used the cost of both electronic and mechanical ASD systems.

The study showed that mechanical ASD systems have the quickest payback, that electronic drive systems have the highest dollar

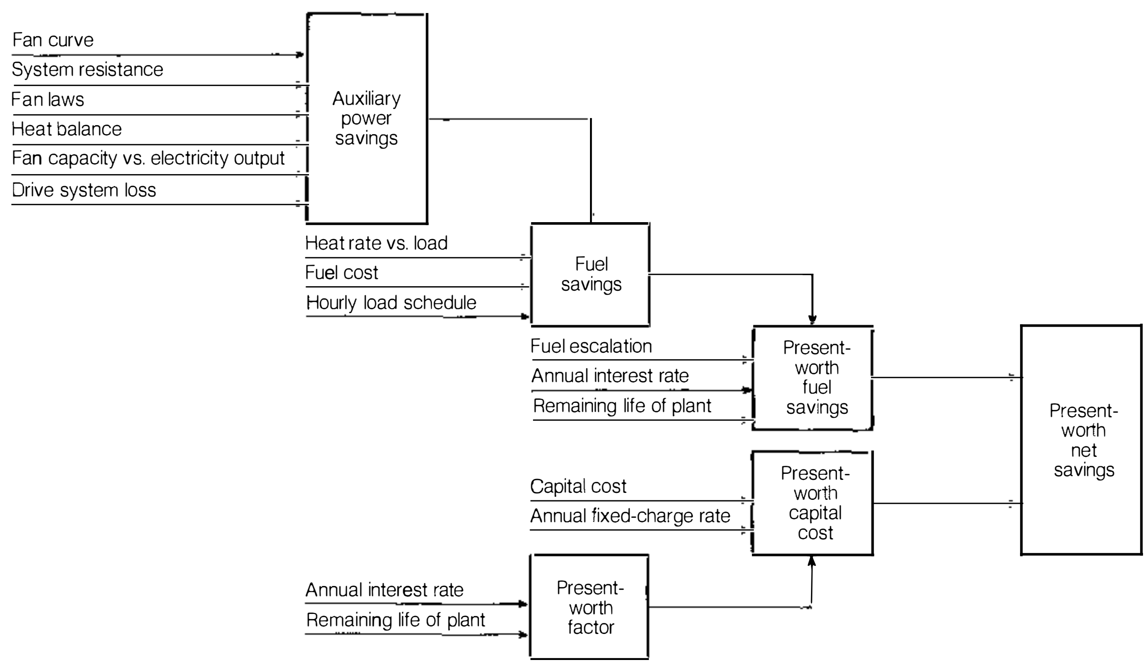


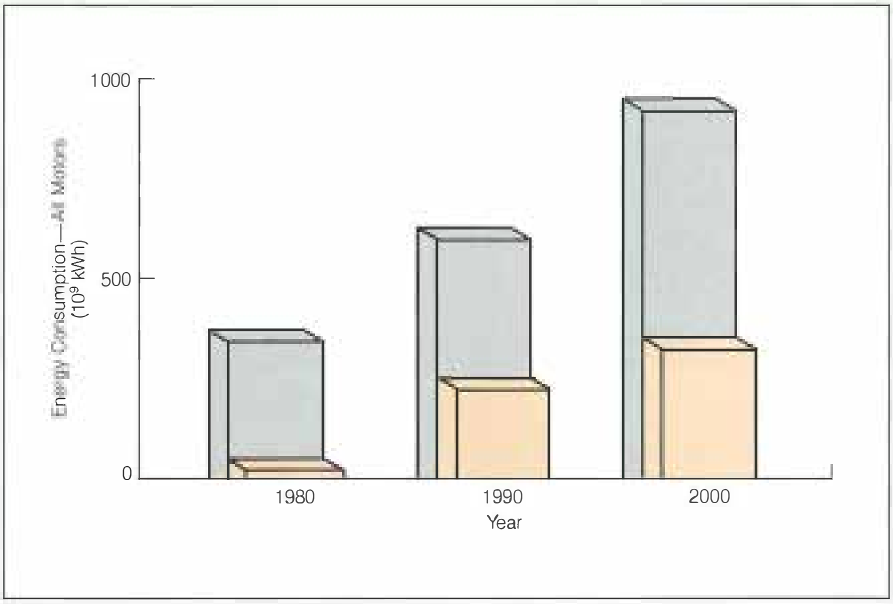
Figure 1 Present worth of energy savings. Essentially, the calculation converts the energy saved in the mechanical throttlers to reductions in fuel consumption and compares the sum of the annual fuel cost savings for the remaining life of the plant with the cost of the ASD equipment, including installation and any company overhead costs. The comparison of savings and costs is carried out in present-worth arithmetic, which is often used in utility economic studies.

return, and that gas- and oil-fired load-cycling units are the most economic for retrofits. Some load-cycling coal-fired plants are economic with ASD conversions, depending on their load curve, fuel cost, and other economic factors. Baseload coal-fired plants generally do not produce enough savings to justify equipping large motors with ASDs, but ASDs may be valuable for solving other problems, such as reducing surrounding noise levels or lowering fan blade erosion from fly ash particles.

The most practical choice for power plant motor retrofit is the induction motor electronic drive, which can be installed in the power supply to the motor. This drive system requires no motor foundation changes, as do mechanical ASD couplings, and allows the use of the existing induction motor.

Based on the opportunities for fuel cost savings shown by the study, EPRI expanded the project to include field tests with participating utilities to demonstrate economics, reliability, and ease of installation (RP1966-06).

Figure 2 Projected energy consumption by fans, compressors, blowers, and pumps, 1980–2000. Color bars represent consumption with ASDs; gray bars, without ASDs. (Source: Resource Dynamics Corp. working paper, "Industrial Electrotechnology Electricity Projections," August 1984.)



Early field test results

The first of the utility ASD retrofits to become operational was at Sierra Pacific Power Co.'s Fort Churchill station, located 70 miles southeast of Reno, Nevada. The station consists of two 110-MW gas/oil-fired units. Unit 2 provides spinning reserve; that is, it runs at minimum load but is capable of system support to compensate for loss of a transmission line or for loss of generating capacity. The difference in fuel cost between gas and coal or economy power purchases makes reducing this minimum load very attractive.

On February 12, 1985, Sierra Pacific successfully completed acceptance testing for conversion of a Fort Churchill station boiler feedpump to adjustable-speed operation. A power electronics ASD was installed to drive the existing induction motor. The ASD has lowered the minimum load on the unit by 4 MW, saving $800,000 per year in fuel. Additional fuel savings that result from removing feedwater control valve losses will increase the total savings to more than $1 million annually. These fuel savings will easily offset the $375,000 installation cost in less than six months.

Fort Churchill is the first of a series in the EPRI team approach to ASD retrofit field tests designed to demonstrate the reliability and application benefits of commercially available ASDs on power plant pumps and fans. The Fort Churchill team includes Sierra Pacific, EPRI-Bechtel, and General Electric Co. (Sierra Pacific had selected General Electric to provide the ASD package.) Iowa Public Service Co.'s George Neal Unit 2 will be the next ASD retrofit and will involve a sliding pressure conversion with ASDs on two 7000-hp boiler feedpumps. These conversions will aid EPRI's assessment of the ASD technology.

EPRI and Bechtel are evaluating several other utility ASD retrofits for induced-draft fans, forced-draft fans, primary air fans, gas recirculation fans, and condensate pumps. In addition, EPRI and the CRS Sirrine Co. are identifying industrial customers who may benefit from ASD applications (RP1966-4). During April EPRI-Sirrine teamed with TVA and the city of Columbia to retrofit the aeration system at the Columbia Waste Water Treatment Plant with electronic ASDs. By eliminating mechanical throttling and controlling compressor air flow by varying compressor speed with an ASD, the team estimates that over 500,000 kWh a year can be saved. In addition to energy savings, reduced maintenance on compressor drive motors because of the soft-start characteristics of the ASD should lengthen the life of compressors, motors, and switchgear.

ASDs are being used where processes require speed control, where applications can result in significant energy savings, and where soft-starting may reduce wear and tear on system components. Applications requiring speed control include conveyor systems in the food processing, paper, automobile, and consumer goods industries. Energy savings potential is high in pumping and air-handling applications. ASDs are now used in pumping applications in the chemical, oil refining, pulp and paper, and food industries.

The U.S. market for utility and industrial ASDs is growing dramatically. At present, more than 100,000 units rated at less than 50 hp are in use; several thousand units rated between 100 and 200 hp are in service. A few hundred units rated at more than 2000 hp are either on order or are operating, mostly in utility applications. A few units as large as 80,000 hp are operating as starters on large pumped-hydro units.

Strong growth in ASD applications is expected over the next decade for pumps and for air handling in the 20–200-hp range as the cost per horsepower continues to decline. Current use of ASDs is far below the potential that exists for energy saving and problem solving. From an estimated 21 billion kWh controlled by ASDs in 1980, ASDs are projected to control some 387 billion kWh by the turn of the century, an amount greater than all electricity used in the process industries today (Figure 2).

To keep utility and industrial engineers apprised of the latest information available on ASDs, EPRI prepared the *ASD Directory*, which is available from Resource Dynamics Corp., 1340 Old Chain Bridge Road, McLean, Virginia 22101—(703) 356-1300. This publication lists ASD manufacters by hp category and will provide an outline of type of drive technology and cost for ASDs from 15-hp to 20,000-hp applications. The *ASD Directory* explains where ASDs can fit into an operation, what they are likely to cost, who is selling them, and how to determine how much energy they can save. *Project Manager: Ralph Ferraro*

R&D Status Report
NUCLEAR POWER DIVISION

John J. Taylor, Vice President

ULTRASONIC PIPE INSPECTION

Boiling water reactor (BWR) piping components are susceptible to intergranular stress corrosion cracking (IGSCC). This cracking is usually discovered by ultrasonic testing (UT) methods during periodic in-service inspections. The method requires a combination of talents, skill, and psychological disposition. Basically, it is a manual method involving a human operator trained to hand-scan an area of concern around pipe welds with a UT instrument, which affords the necessary signals for human interpretation. Inherent limitations of manual UT have brought to light several considerations that have formed the basis for development of automated UT systems.

Primary to the inspection activity is concern about radiation exposure. A UT inspector is always in close proximity to radiation sources. Biologically, the inspection time is limited and psychologically stressful. Both these conditions, along with inherent human variability, combine to make accurate manual inspections difficult.

Recording of data is normally through the media of charts, graphs, and diagrams; entries to those media are prescreened by either operator judgment or preset rules. Thus, only an imprint or outline of pipe conditions is available. In addition, because of the considerable amount of information available by UT, the thought and computation burdens for a human are overbearing, and only certain operator-defined key characteristics of the UT signal can be rated at any one time. This may lead to ambiguous decisions regarding the condition of a pipe (i.e., decisions based on sparse input data are often in conflict). These are considerations that define the opposite of the inspection setting one would like to have.

The answers to the following issues are evolving through the probing of automated and computer-aided options.

- Reduction of radiation hazard and psychological stress
- Abundant information-processing capability
- Consistent decisions regarding the same UT signal
- Ability for repeated review of high-density, detailed information at an analytic pace

Numerous cases of pipe cracking have been discovered in BWRs in recent years. These incidents have provided impetus for the rapid introduction of advanced ultrasonic pipe inspection systems. Such systems are typically equipped with remotely controlled electromechanical scanners, are interfaced with computers, and have data storing and retrieval capabilities. Some systems also have decision-making capabilities. The objectives of these developments are the reduction of radiation exposure and the increased reliability of inspection results.

Advanced pipe inspection systems may be divided into two main categories: feature-based systems and imaging systems. Feature-based systems extract parameters, or features, from ultrasonic waveforms and allow an inspector to make judgments by referring to correlations that have been discovered between various features and physical properties related to the structural integrity of a piping component. Imaging systems employ the data obtained from high-density ultrasonic scans of an inspection zone in order to construct color-coded images of the material surrounding a weld. These images give an inspector a map of material flaws. Using other information relating to spatial location, echo strength, probable stress condition, and so forth, along with the image presentation, enables increased reliability in decision making. Within the last two years several such systems have passed the NRC Bulletin 83-02 requirement for the detection of IGSCC.

The first system to pass such criteria was CUDAPS (computerized ultrasonic data acquisition and processing system). CUDAPS comprises an automatic pipe scanner, a scanner controller, a specialized configuration of computer hardware and software, and a pulser-receiver unit. The scanner, AMAPS, was specifically designed for pipe scanning by Amdata, Inc., with EPRI funding. Most automated systems developed to date use AMAPS. The computerized configuration allows the operator to preprogram scan patterns and other data acquisition parameters. The scanner can be remotely positioned by using a cable-joystick combination. As an option, the computer (ALN 4060) can be programmed to recognize certain classes of reflectors by using a statistically derived combination of features. Field experience with CUDAPS was gained at two sites—the James A. Fitzpatrick plant in Scriba, New York, and the Edwin I. Hatch plant in Baxley, Georgia. All components of CUDAPS were developed under RP1125-1 and RPT104-1 and are now commercially available. Amdata Systems, Inc., of San Jose, California, supplies the hardware necessary for scanning and computer interfacing. General Research Corp. of Santa Barbara, California, supplies the ALN 4060 flaw discriminator.

IntraSpect was the first automated, remotely controlled ultrasonic pipe inspection system to pass the unlimited NRC qualification test. IntraSpect is a combination imaging, data acquisition, and data retrieval system. It uses an AMAPS scanner in preprogrammed pattern modes to collect ultrasonic data for image production. The resultant images are color-coded according to amplitude response and are spatially consistent with the actual inspected piece; they are therefore useful as aids for inspectors. Radio frequency waveforms acquired during scanning are stored on floppy disks and may be viewed in a superposition mode on the image scope. The value of the data acquired is largely due to the retention of positional information, such as the relative position of the UT probe with respect to the flaw. This device was developed with BWROG II funding and has been used at the Edwin I. Hatch plant and the Savannah River production facility. IntraSpect is also available through

Amdata Systems, Inc. Several IntraSpect systems have been purchased by the Tennessee Valley Authority.

Pacific Gas and Electric Co. originally contracted Dynacon Systems, Inc., for the development of the ultrasonic data recording and processing system (UDRPS). EPRI supplied funding for improvements to this system (RP2165-3). UDRPS is a multichannel target-tracking imaging system. It contains software that directs scanning, so if a target reflector is present, the target will always be included in the scan. The system derives its computing power from a Hewlett-Packard 1000 computer. It also uses an AMAPS scanner, although in much faster modes than does the IntraSpect system. Position-annotated images are available with this system, along with three-dimensional views of those configurations that are amenable to the required scanning. The UDRPS system is available either as a product or as part of an inspection service package. It is offered by Dynacon Systems, Inc., of Concord, California. This system has been purchased by Baltimore Gas and Electric Co.

Ultra Image III, a scanning and imaging system developed by General Dynamics Corp., has been adopted and modified by General Electric Co. for use as a component of its inspection system, GEDAS (General Electric data acquisition system). Originally, Ultra Image was used for high-density normal A-scans. (*Normal* means that the sound energy enters the part to be scanned at right angles to the part surface. *A-scan* means that an amplitude as a function of depth in material record is generated.) The amplitudes thus obtained were then color-coded. General Electric modified Ultra Image to handle the angle beam (entry of sound at angles other than 90°) inspection modes required for nuclear piping configurations.

A novel system for obtaining position-annotated ultrasonic data has been developed by Southwest Research Institute. Its system has been dubbed SUTARS (search unit tracking and recording system). The ultrasonic transducer housing is equipped with two sound-emitting beacons. The SUTARS operator first mounts a track or belt of sound receivers on the pipe to be inspected and then scans manually. The transducer position is obtained from the beacon signals received by the pickup track. When ultrasonic data are designated to be recorded, position information is recorded simultaneously. Data are stored on a portable cassette system; the cassettes can be uploaded to a larger computer processing system for analysis and hard-copy output.

A semiautomatic inspection system, ALARA I, has been configured by Virginia Corporation. ALARA I consists of a remotely controlled scanner that is equipped with an automatic couplant feed system. (Transducers are coupled to parts with a sound-conducting gel called couplant.) All data are read from ultrasonic instruments and manually recorded. Interpretation is the same as in standard manual inspections.

European efforts have materialized into ROBIE, ZIPSCAN, and P-Scan. ROBIE is a system that has a joystick-controlled scanner and standard ultrasonic instrumentation. ROBIE was developed by the Kraftwerk Union Ag of Germany and is similar in concept to ALARA I; it has remote automatic scanning with manual data recording and human interpretation. ZIPSCAN is a product of the United Kingdom Atomic Energy Authority Harwell Laboratory. ZIPSCAN is akin to GEDAS. It can perform high-speed averaging of up to 256 waveforms. If desired, waveforms can be stored and displayed. The Danish Institute of Welding developed P-Scan, or projection scan, for its inspection protocol. This device produces scan images that are representative of planes cut at right angles to the scan surface and parallel to the surface.

EPRI is continuing its efforts to advance the utility of computer-aided pipe inspection systems. The lessons learned through experience with automated systems suggest combining the capabilities of feature-based and image-based systems. The evolving field of expert systems is also receiving consideration along these lines. The operators, whose opinions will eventually form the final decision, use thought processes based on feature values, images, past experience, strategies, and so on. Feature-based systems are supplying key variables to the inspectors and imaging systems guidance on spatial locations of reflectors. Expert systems may be able to supply the recipes for combining these two inputs to reduce the speculative nature that is often associated with manual inspection.

Advanced pipe inspection systems are highly cost-effective. They significantly reduce outage time, personnel exposure to radiation, and the number of inspection personnel. They also provide permanent, low-cost data storage for future reference. *Project Managers: Gary Dau, Mohamad Behravesh, Soung-Nan Liu, Michael Avioli*

New Technical Reports

Each issue of the *Journal* includes information on EPRI's recently published reports.

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

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Goodnoe Hills MOD-2 Cluster Test Program
AP-4060 Final Report (RP1996-6); Vol. 1, $14.50; Vol. 2, $14.50; Vol. 3, $11.50
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Proceedings: Turbine Bearings and Rotor Dynamics Workshop
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Proceedings: Pressurized Fluidized-Bed Combustion Power Plants
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ELECTRIC POWER RESEARCH INSTITUTE
Post Office Box 10412, Palo Alto, California 94303

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