The Science of Global Warming

ELECTRIC POWER RESEARCH INSTITUTE

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Also in this issue • Wind Power • Operator Training Simulator • Troubleshooting Combustion Turbines

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Cover: A special radiometer operated from NASA's Nimbus-7 satellite maps the distribution and concentration of phytoplankton, free-floating aquatic plant life that plays a significant role in global uptake of CO_2.

Getting Proactive on Greenhouse Research

We have known for over a decade that the accumulation of greenhouse gases in the atmosphere and its potential effect on climate pose difficult scientific questions. As this month's cover story points out, clouds, ocean currents, solar activity, and terrestrial and aquatic life all appear to be involved in a complicated web of change dynamics and feedback processes.

One could question the advisability of trying to sort out this difficult puzzle were it not for the fact that the issue is as broad in consequence to public policy as it is in its mix of scientific disciplines. Some have speculated that even moderate climate change could disrupt the economic and social infrastructures of entire nations—including ours—by shifting agricultural, energy use, and demographic patterns. Given the uncertainties in predictions, precipitous, widespread action to avoid such potential problems carries its own dangers. Analyses of the economic consequences of reducing carbon dioxide emissions by 20%, as suggested by recently proposed initiatives, estimate costs to be 1–5% of the gross national product for the United States, and the impact for some developing nations is expected to be much higher.

The electric utility industry, as a visible producer of carbon dioxide, will almost certainly be one of the first targeted for emissions reduction in any greenhouse legislation put into place. This is problematic, since the technical knowledge needed to formulate a legislative response that is clearly both effective and economically prudent will probably not be developed in this decade. Nevertheless, I believe the power industry can and should take a proactive stance. As providers of a key element in our nation's quality of life, we must be responsive not only to the technical needs of society but also to the cultural directions deemed important to its health and welfare.

In support of a proactive policy, I suggest a three-pronged approach for research. First, EPRI should accelerate the study of global climate change to ensure that decision makers have access to absolutely the best scientific information, no matter when decisions are made. Second, EPRI should actively pursue cost-effective strategies and options for mitigation and ensure that the energy and economic consequences of such steps are clearly represented. Finally, EPRI should explore what might be required of the power industry and the nation as a whole to productively adapt to climate change, should it prove to be inevitable.

Showing leadership on the climate issue will do more than ensure that our industry's position is considered in any decisions that are made; it will also ensure that we are prepared—in very real terms—for whatever outcome materializes. With an issue like global warming, such preparation may be the best investment we can make.

G. M. Hidy

George M. Hidy, Vice President
Environment Division

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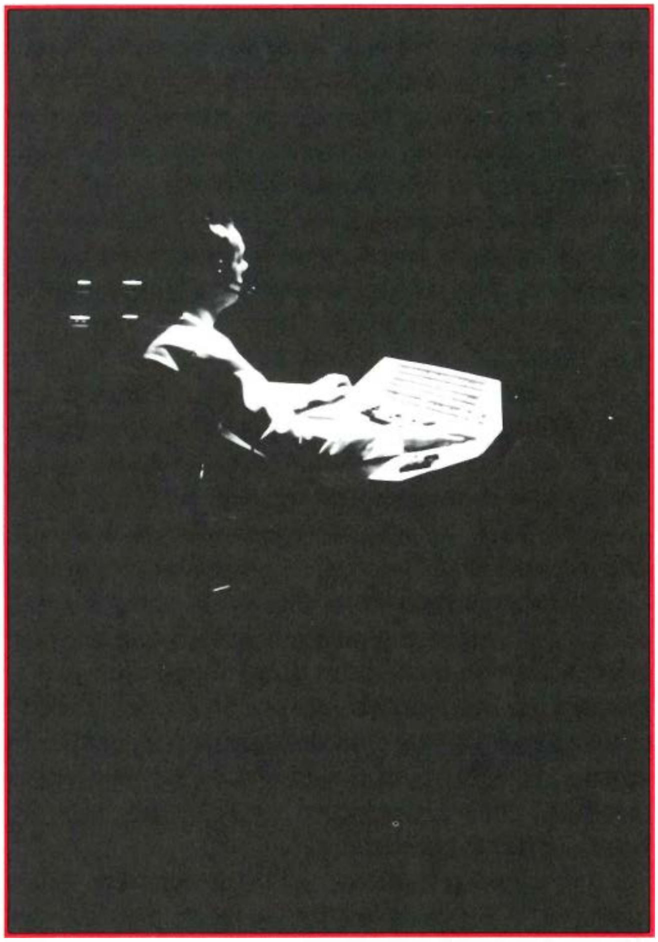

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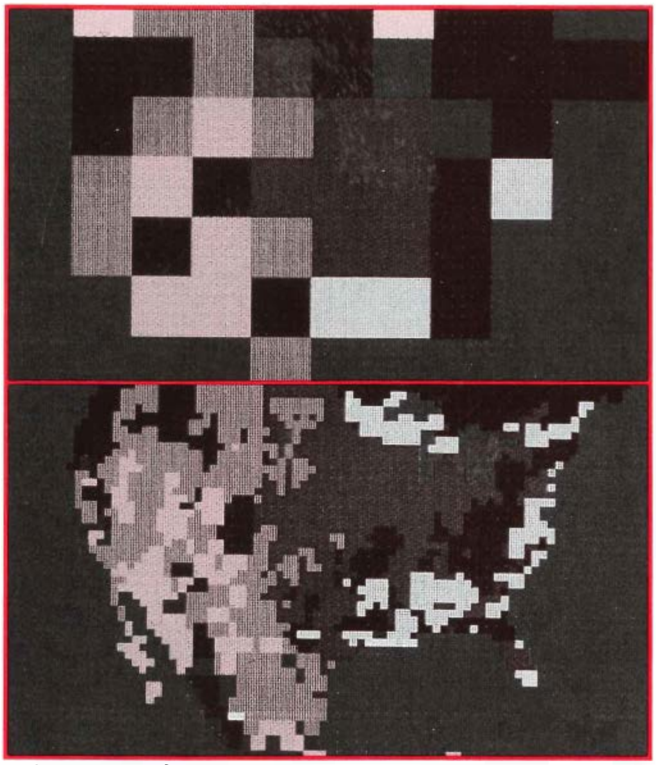

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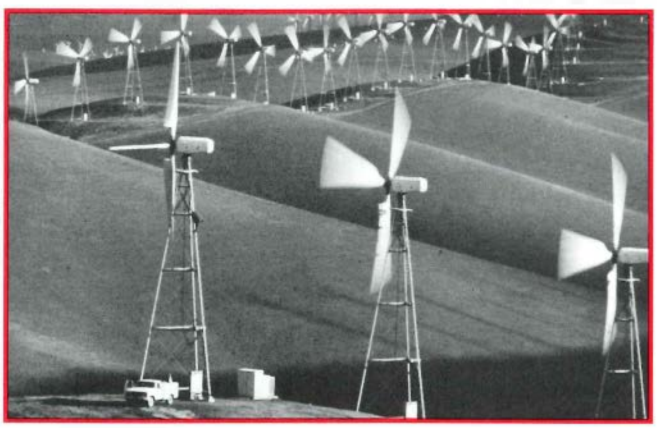

EDITORIAL

Getting Proactive on Greenhouse Research

COVER STORY

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Research is turning up interesting new insights on the mechanisms that may drive global climate change; representing these factors accurately in comprehensive climate models will be key to steering an effective course of response.

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As wind energy comes of age as a proven, nonpolluting renewable resource, EPRI is supporting a promising effort to develop the kind of advanced turbine required for wider geographic application.

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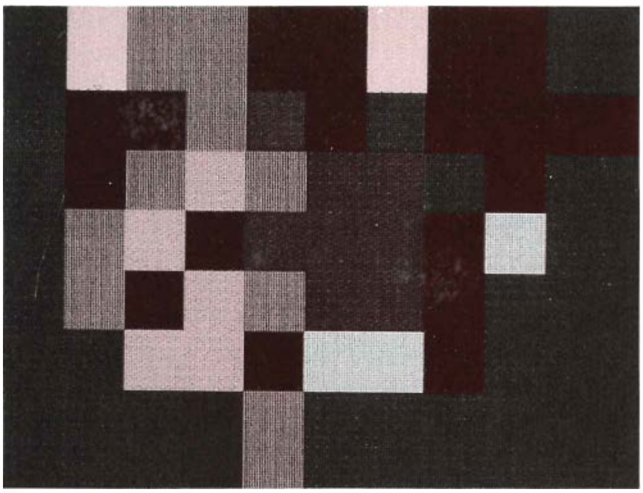
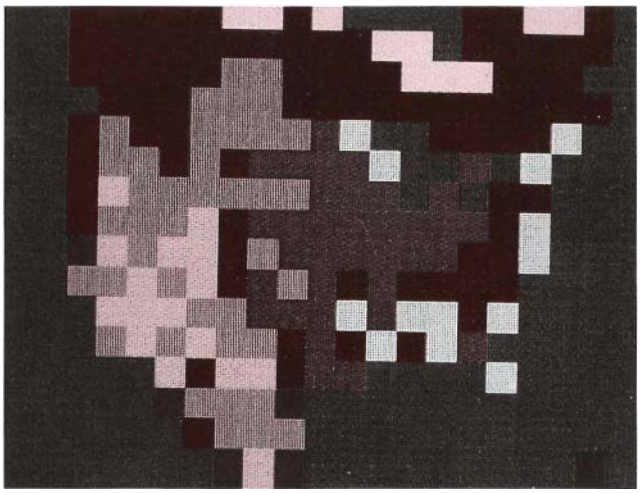
Using realistic system software and a control room twin, a new operator training simulator can hone dispatchers' basic skills and safely drill them on dealing with real-world emergencies.

Sharper Focus on

Spatial resolution is a central problem in modeling climate change. The general circulation models presently in use divide the world into a grid of cells, each about 500 kilometers on a side. Such coarse division tends to overgeneralize and blur important features—for example, terrain eleva-



500-km resolution



250-km resolution

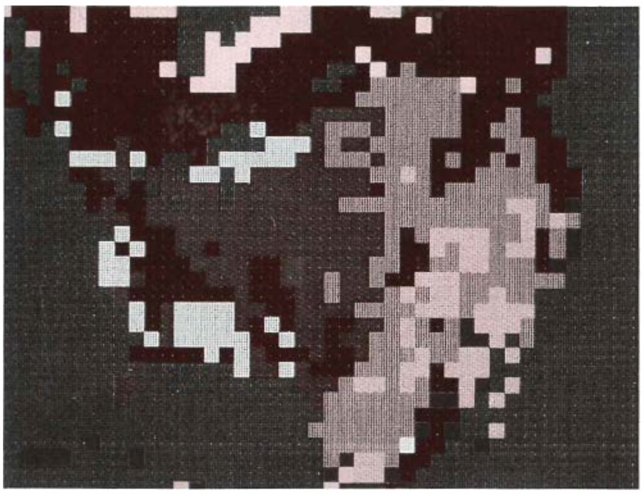
While much has been learned about the greenhouse effect over the last few years, enough uncertainty still remains to support strong debate. Many prominent scientists are convinced that the continuing buildup of greenhouse gases will lead to significant and inevitable global warming, but there has been a surge of dissenting, or at least cautionary, voices in the scientific and political communities about the severity of the problem and what would be the appropriate countermeasures. Much of the debate has centered around current scientific understanding of natural climate cycles, feedback mechanisms, and environmental resiliency and around the mathematical models used to represent such factors.

Getting better answers in these areas will be particularly important for the electric power industry. Utilities are already being targeted by proposed legislation designed to produce stringent reductions in greenhouse gas emission. In addition, if average temperatures do start to rise, utility operations will be directly affected as patterns of both electricity supply and demand begin to shift. Also, because electricity has such a pervasive influence throughout the economy and is linked so closely to productivity and well-being, utilities will inevitably play an important role in the broad societal response to any climate change that does occur.

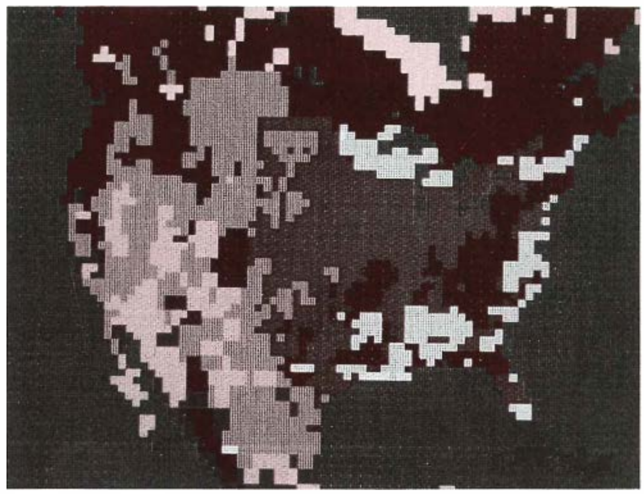
"Federal research on climate is large but very diffuse," points out George Hidy, vice president for EPRI's Environment Division, "so our goal is to concentrate on those aspects of most interest to utilities. The mood in Congress is clearly to make dramatic reductions in carbon dioxide emissions through changes in the generation and use of energy. Our aim is to provide the industry with the information it needs to ensure that these decisions are based on good science and economics. At the same time, I believe that any solution to the buildup of

Greenhouse Science

tion, shown here. Usable predictions of climate change on a regional level will require a much finer grid, but each doubling in resolution will increase the computational requirements by at least a factor of 4.



125-km resolution



62.5-km resolution

greenhouse gases will ultimately involve even greater electrification of the economy. Utilities thus have a major new opportunity to work with their customers to enhance the efficient use of electricity."

Continuing debate

The so-called greenhouse effect is a natural atmospheric phenomenon whose warming of the earth's surface makes our planet habitable. Only about one-third of the solar energy impinging on the earth is reflected back to space directly; the rest is absorbed by the atmosphere and the earth's surface and re-emitted as infrared radiation. Relatively small amounts of trace gases—including carbon dioxide (CO_2), methane, nitrous oxide, chlorofluorocarbons, and even water vapor—absorb some of this infrared radiation, heating the atmosphere. Steady increases of some greenhouse gases because of human activity have caused the current concern that the natural climate balance might be upset, resulting in unprecedented global warming near the earth's surface.

Since the beginning of the Industrial Revolution, the level of CO_2 in the atmosphere has increased about 25%. During the same period, the average global temperature appears to have risen by about 0.5°C, although not steadily. Some atmospheric scientists have concluded that this warming is largely a direct result of the increase in CO_2 and other greenhouse gases. At the present time, about the same amount of CO_2 that entered the atmosphere during the century from 1850 to 1950 is being emitted every dozen years. If such emissions go unchecked, the combined greenhouse gases are expected to reach the radiative equivalent of a doubling of CO_2 from preindustrial levels in 40 to 60 years. According to some global climate models, such a doubling would commit the earth to an eventual warming of about 2°C, even if CO_2 rose no further.

Such interpretations of the historical temperature record and projections of

THE STORY IN BRIEF

Growing popular and congressional activity has upped the urgency of narrowing the scientific uncertainties of greenhouse warming. Reflecting this heightened concern, President Bush recently proposed increasing the budget for federal research on global climate change to over a billion dollars for the 1991 fiscal year. New information on greenhouse mechanisms has been developed, with interesting findings regarding cloud effects, ocean dynamics, and forest influences, but the development of climate models that better represent these and other factors will be key to making informed decisions on environmental policy. While the federal program is by far the largest component of the national effort, EPRI is adding its expertise in several important areas, including studies of the earth's environmental history and experimental work on the response of vegetation to CO_2 buildup. An article on mitigation options and their likely costs will appear in the Journal *later this year.*

future warming continue to be examined in technical forums as new observations become available. For one thing, no one is quite sure what to make of the most recent data on global temperatures. According to an analysis of records from ground-based instruments, the 1980s were clearly the "greenhouse decade," with 6 of the 10 warmest years on record. A recently published analysis of satellite data, however, failed to detect any warming trend during the decade. Rather, this analysis of global temperatures from the TIROS-N series of weather satellites revealed dramatic year-to-year changes but no net change from 1979 through 1988.

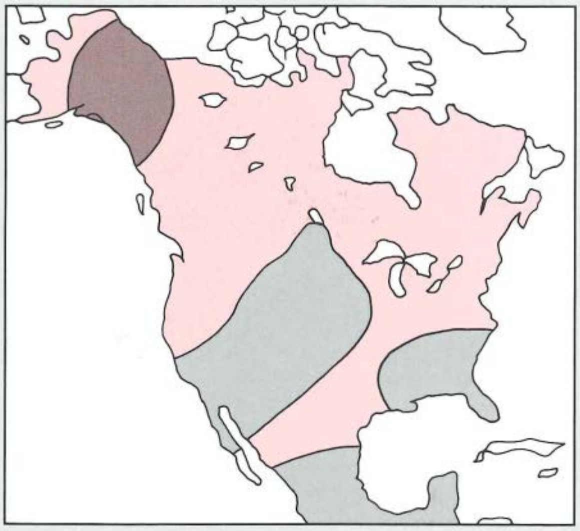
One of the most politically influential and most controversial critiques of the theory that human activity is leading to global warming has been published by the George C. Marshall Institute. The authors (as well as other scientists) note that surface temperatures over the last century have not risen steadily and, in fact, declined from about 1940 to 1970—a period during which greenhouse gas emissions accelerated. The Marshall Institute report claims, however, that one indicator of sunspot activity declined during this same period, suggesting a possible relationship between the observed cooling and reduced solar energy reaching the earth.

On the basis of this and other evidence, the authors conclude: "In fact, it is possible that a combination of natural and solar variability is the cause of the entire temperature increase observed since 1880, with the greenhouse effect relegated to a negligible role."

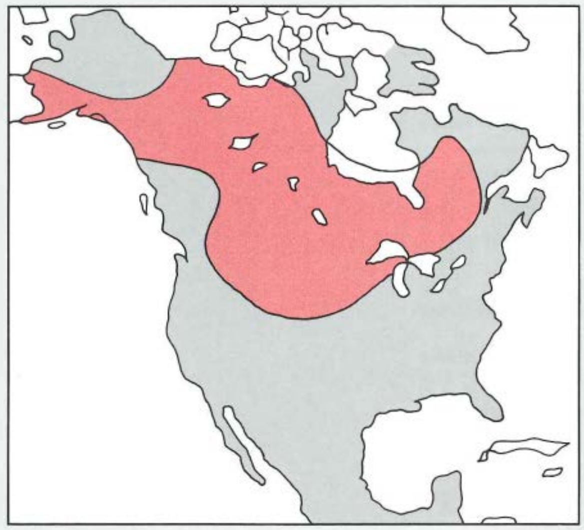
The Marshall Institute document has reportedly been influential among policymakers in the Bush administration, which has so far taken a cautious approach to the greenhouse issue. On the other hand, several prominent scientists have severely criticized the report for leaping to unsupported conclusions and ignoring alternative explanations of the data. Jerry Mahlman, director of the Na-

Variation Among Models

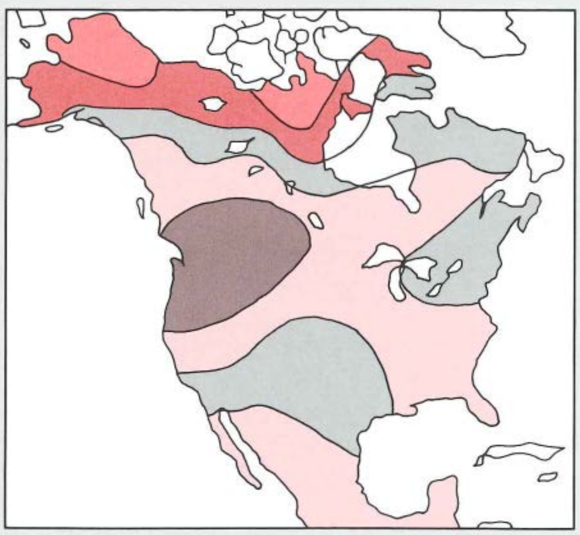
Predictions made by today's general circulation models typically show a great variation in outcome. In these projections of changes in summer soil moisture that would result from a doubling of atmospheric CO_2, the results of four major models show almost no commonality in pattern or degree. Soil in the midwestern breadbasket region is forecast as wetter or drier, depending on the model used.



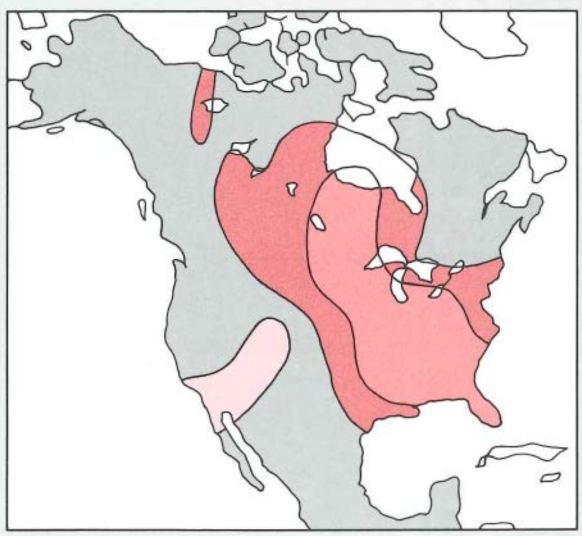
National Center for Atmospheric Research



Geophysical Dynamics Laboratory



Goddard Institute for Space Studies



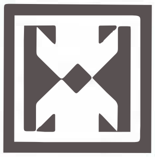
United Kingdom Meteorological Office

CHANGE IN SOIL MOISTURE

- >2-cm increase
- 0 to 2-cm increase
- 0 to 2-cm decrease
- 2-cm to 4-cm decrease
- >4-cm decrease

Critical Influences

Predicting how climate change may occur and finding ways to mitigate the changes depend on a better understanding of several key variables, each of which has become the subject of intense research.



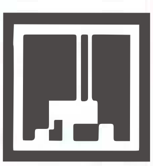
Ocean-atmosphere interaction Oceans exchange heat energy with the atmosphere and transport it via globe-girdling currents in ways that are not well understood.

Clouds Clouds can help either heat up the earth or cool it, but which influence would dominate if global warming produces more clouds remains unclear.

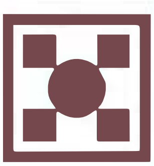
Incident solar energy Both solar variability and changes in the earth's orbit affect the amount of energy reaching the atmosphere from the sun.

Biosphere response As CO_2 levels rise, climate change could be naturally mitigated by the accelerated growth of terrestrial and aquatic plants, which absorb this gas.

Deforestation Massive tree-cutting in tropical and temperate forests is exacerbating the buildup of greenhouse gases, but the cumulative damage is hard to quantify.



Energy mix Although adding more nuclear and solar generation could reduce CO_2 emissions, developing countries are expected to increase the global use of fossil fuels dramatically.



Other gases The combined effect of other greenhouse gases, such as methane and nitrous oxide, is thought to be as large as that of CO_2 in overall greenhouse warming.

tional Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory, took strong issue with the document in *Science* magazine, observing: "There are uncertainties, but I can't think of any combination of them that could conspire to make the [greenhouse] problem go away."

"Clearly, more research will be needed before a consensus emerges within the entire scientific community over the increasing greenhouse effect," says Leonard Levin, a climatologist in EPRI's Environment Division. "The Marshall Institute report and others have pointed out some of the scientific uncertainties in our discussion of what has caused the reported temperature changes over the last hundred years. But we're still just talking about alternative hypotheses. Reanalysis of what is already known can take us only so far. Our most important need now is for better hypothesis testing, more data, better models, and a framework for comparing them."

Modeling the environment

Because of the sheer volume of calculations involved, climate modeling remains a daunting task. Current practice involves calculating averages for variables like temperature, cloud cover, land-surface altitude, and humidity over areas approximately 500 kilometers on a side. The use of such large areas means, in effect, that mountain ranges are flattened and interior deserts are lumped together with rainy coasts. The grid point lying at central California in one model, for example, averages data from San Francisco Bay through the Sierras to the middle of Nevada. Such coarse resolution severely limits the ability of so-called general circulation models (GCMs) to predict regional climate effects. Even so, a single century-long climate forecast may require months of processing time on a state-of-the-art supercomputer, sharply limiting the number of scenarios that can be considered.

Within these limits, the present generation of GCMs do generally agree on some key results that could be expected from a doubling of atmospheric greenhouse gases. All predict some overall warming of the earth's surface, but the range of projected increases in temperature varies quite widely among individual models—from less than 1.5° to more than 4.5°C. Some consensus does seem to be forming, however, that an increase at the lower end of this range is more likely. At a recent meeting of the National Academy of Science's Panel on Policy Implications of Greenhouse Warming, for example, most panelists said they expected temperature increases around 2°C from a greenhouse gas doubling.

Another major area of agreement among the GCMs is that greenhouse warming will be more pronounced at higher latitudes, while the tropics will experience less effect. This development could prolong the growing season for crops in some regions, for example, the Ukraine and the northern Great Plains of North America. Such benefits might be canceled out, however, by the drier summers and more frequent heat waves projected for midlatitude continental interiors as storm tracks migrate northward. The various models do not agree very well on how specific regions might be affected by these overall changes.

Even when the GCMs agree, their results may not accurately predict the future because of major uncertainties about critical climate processes and the assumptions modelers must make to accommodate these gaps in knowledge. Three of the most important climate influences that are now highly simplified in all GCMs involve cloud behavior, ocean dynamics, and carbon exchange processes.

Clouds can either help warm or help cool the earth, depending on their form. All clouds reflect sunlight and thus exert a cooling influence, but they also trap infrared radiation emitted from the earth's surface below, which has a heating effect. Low-level stratus and midlevel storm clouds tend to cool more than they warm; high-level cirrus clouds tend to be net warmers.

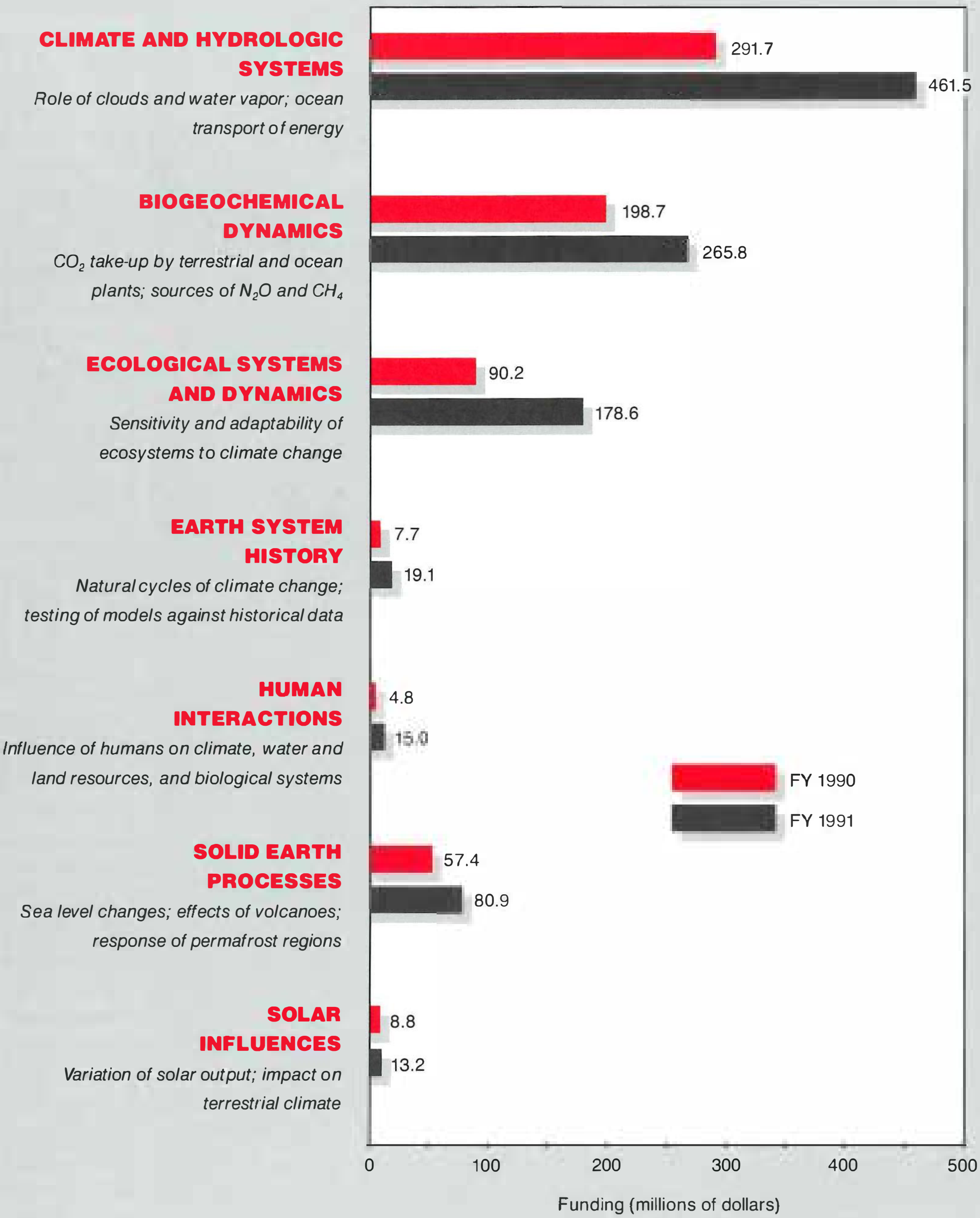
Until recently the overall contribution of clouds to the earth's thermal balance had not been measured, and most GCMs use highly simplified cloud modeling that predicts a net heating effect. Satellite data taken as part of the Earth Radiation Budget Experiment (ERBE) now indicate, however, that clouds exert a net cooling influence on the planet as a whole, with the effect being much stronger at midlatitudes than in the tropics. This conclusion is still tentative because only a few months of ERBE data have so far been analyzed, and considerable caution is required in applying these results to climate change. Increased evaporation from global warming would probably result in the formation of more clouds, but whether new cloud patterns would provide a positive or negative feedback remains unclear. Nor is it certain how big an impact the resulting warming or cooling effect would have on the general warming trend.

Oceans, as far as many GCMs have been concerned, are more or less huge swamps—uniform, motionless, and only loosely coupled to the atmosphere. In fact, however, globe-straddling oceanic currents function as a huge conveyor system, transferring heat from one latitude to another. One cold, deep current of very salty water stretches from the North Atlantic all the way around the southern extremes of Africa and Australia, finally upwelling in the mid-Pacific. Complementary currents bring warm, shallow water from the Indian Ocean into the Atlantic and around the tip of South America.

Recent studies of sediment cores from the North Atlantic indicate that these currents can undergo changes and produce a dramatic effect on climate. As fresh water from melting glaciers began to flood the North Atlantic at the end of the last ice age, some 10,000 years ago,

Federal Greenhouse Research

At $1.034 billion, proposed 1991 funding for the government's U.S. Global Change Research Program is 57% higher than the 1990 level of $659.3 million. About half of the new budget would be devoted to satellite-related research.

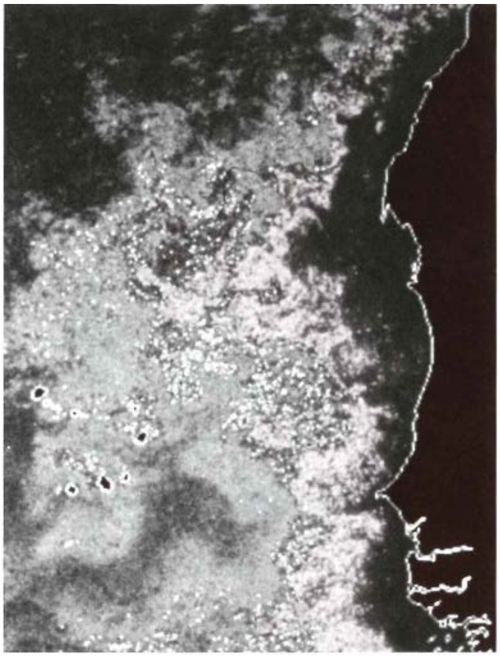


EPRI Works on Greenhouse Science

Major greenhouse research at EPRI includes a study of past atmospheric composition, determined through analysis of air bubbles trapped for hundreds of years in glacial ice, and a variety of experiments investigating plant and ecosystem response to elevated levels of CO_2. EPRI is also involved in studies of historical temperature trends, ocean-atmosphere interactions, reforestation, heat transfer by ocean currents, phytoplankton CO_2 uptake, and ecological effects of climate change.

Reforestation

Phytoplankton studies



Glacial ice coring

Plant response to CO_2

the ocean's salinity apparently decreased enough to interrupt the deep "conveyor" current. The result was a thousand-year cold snap in Europe called the Younger Dryas, which took less than a century to develop and perhaps as little as 20 years to reverse. On the basis of this evidence, researchers have concluded that ocean dynamics can play a critical role in sometimes rapid transitions from one relatively stable climate state to another. In the current context, their work raises a disturbing possibility—that greenhouse warming could melt Arctic Ocean ice and decrease the salinity of the North Atlantic enough to slow the Gulf Stream, creating another severe cold snap in Western Europe.

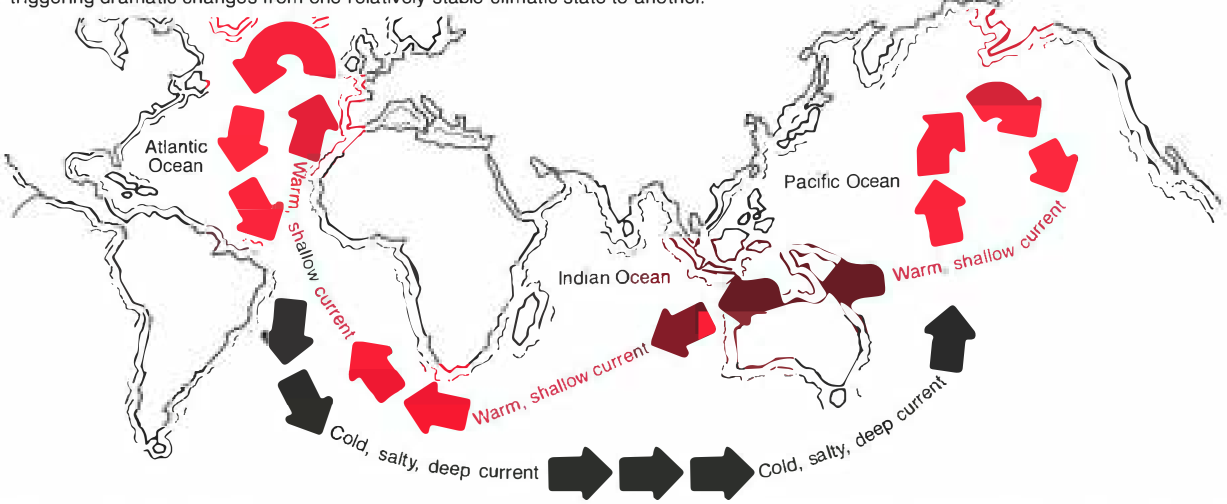
Smaller but more common climate modifications have also been found to have links to changing ocean conditions. The El Niño phenomenon, for example, involves important shifts in trade winds and prevailing storm tracks caused by shifts in the pattern of ocean-atmosphere interactions. The challenge for climate modelers is to accommodate such ocean influences in their GCMs. In particular, they need large amounts of new data to address such questions as these: How much additional greenhouse heat can the oceans absorb, and how fast? Where will this heat be taken by ocean currents? What local climate effects will result in various parts of the world?

Ecosystem response is potentially an important wild card that could upset predictions of how climate will change as a result of mounting greenhouse gases. Although the ability of plants to absorb carbon dioxide and release oxygen through photosynthesis is well understood at the level of individual organisms, the overall importance of terrestrial ecosystems as a potential sink for CO_2 from fossil fuels has long been considered small compared with that of the oceans. No current GCMs calculate the interaction of the atmosphere with the biosphere or attempt to model how this interaction might change with rising temperatures and CO_2 emissions.

This presumption of a minor role has been challenged recently by research indicating that the terrestrial ecosystems of the Northern Hemisphere may absorb two or three times as much carbon from the atmosphere as do the oceans. The vast northern forests appear to play a particularly important role, which

Climate and Ocean Currents

Massive ocean currents essentially act as conveyors that transport heat energy around the world. As a net loss of water from evaporation in the North Atlantic increases the salinity of the ocean surface, the relatively dense surface water sinks, creating a cold, deep current that winds its way around Africa and Australia before upwelling in the Pacific. This movement is compensated by warm, shallow currents flowing in the opposite direction. Recent studies of the last ice age imply that disruption of these currents could be a major influence in triggering dramatic changes from one relatively stable climatic state to another.



prompts new concern over deforestation in this area as well as in the tropics. Other research has also challenged the suggestion that harvesting old-growth northern forests and replacing them with faster-growing younger trees would increase the rate of CO_2 uptake. For intensively managed forests of the Pacific Northwest, the on-site carbon storage capacity is sharply reduced at harvest and does not approach the old-growth capacity for at least 200 years.

Even with these new insights, the task of modeling ecosystem responses to the greenhouse effect remains formidable because there are so many competing processes. The rate of photosynthesis in most plants, for example, is not very sensitive to temperature change but does increase in response to rising CO_2 levels. Conversely, the rate of plant and microbial respiration—a process that occurs simultaneously with photosynthesis and regenerates CO_2—may increase 10–30% with a 1°C rise in average temperature. The production of methane by decay processes in ecosystems can also change significantly as temperatures rise, warming wet soils and stimulating the activity of anaerobic bacteria. More data on a massive scale will be needed before any of these effects can be modeled adequately. A final catch: the very existence of particular ecosystems may be threatened by regional climate changes, such as increased drought, that cannot be predicted accurately by current GCMs.

EPRI initiatives

Both data gathering and model development related to the greenhouse effect are dominated by the federal government's research program. The administration's 1991 budget proposes more than $1 billion for this research, more than half of which would go to the National Aeronautics and Space Administration for satellite-related work. EPRI's climate research program is designed to contribute expertise in a few specific areas of scientific uncertainty that have the greatest impact on decision making about how to manage the greenhouse gas issue. The program includes some support for basic science—particularly studies of historical temperature trends, ocean-atmosphere interactions, and forest response to CO_2—plus measurement of power plant emissions of nitrous oxide, development of mitigation options, and economic analysis of emission constraints. In addition, much of the Institute's ongoing work on generation and end-use efficiency will be key in helping utilities and their customers cope with future regulations and possible climate change.

To help establish a more comprehensive record of greenhouse gases and various air pollutants from before the Industrial Revolution to the present day, EPRI is sponsoring an analysis of gas bubbles trapped in glaciers. This work, now under way at the University of New Hampshire, involves determining the chemical composition of gas samples taken from glacial cores collected in southern Greenland and the Yukon Territory. From this analysis researchers expect to construct a 200-year history of such greenhouse gases as CO_2, methane, and nitrous oxide, together with a record of airborne particles containing sulfates, nitrates, and trace elements. The results can then be used to address some outstanding questions about the origins and emission rates of various greenhouse gases.

Two research projects are expected to get under way this year to help clarify the role of oceans in the greenhouse effect. The first, at Columbia University, will study the "conveyor system" of oceanic currents that transport heat from sea to sea. In particular, this research will focus on the question of whether increases in greenhouse gas emissions could disrupt these currents enough to cause a shift in climate. The second project, at Brookhaven National Laboratory, will seek to determine whether CO_2 uptake by phytoplankton has changed since the Industrial Revolution. Researchers will examine existing records of ocean transparency, collected since 1866 by mariners using simple optical techniques. Since transparency is related directly to the concentration of phytoplankton, the records will indicate whether the number of these tiny, photosynthetic marine organisms has risen significantly over the last century in response to the increased availability of CO_2.

Although individual terrestrial plants grown under ideal conditions generally respond to increased atmospheric levels of carbon dioxide by accelerating photosynthesis and CO_2 uptake (the carbon dioxide "fertilization effect"), little is known about whether the same would hold true for large forest ecosystems if they were under stress from drought or nutrient deficiencies. Such stresses might affect large temperate-zone forests as a result of climate changes associated with the greenhouse effect. To clarify this issue, EPRI is sponsoring studies at the Desert Research Institute and Duke University on how two important forest ecosystems—ponderosa pine and loblolly pine—respond to elevated CO_2 levels when supplies of water, nitrogen, and phosphorus are reduced. The research will involve both controlled-environment and open-top-chamber experiments.

"EPRI is now considering ways in which our research can further the scientific understanding of the greenhouse effect in coordination with the much larger federal effort," says Environment Division project manager Chuck Hakkarinen. "Our specific work on polar climate trends and forest response can help fill important gaps of knowledge."

For example, in another project EPRI is investigating to what degree reforestation and increased plant growth might slow the buildup of CO_2 in the atmosphere. Results have shown that if one-fourth of the land once occupied by forests but now cleared for agriculture or other uses could be reforested, the trees would absorb approximately one-fifth of the CO_2 now emitted by anthropogenic sources. Additional CO_2 could be absorbed through increased growth of seaweeds and halophytes (plants that grow in saline environments, such as sea coasts and inland deserts).

"Clearly, enhanced plant growth is an attractive way to reduce the buildup of greenhouse gases, although there could be institutional and economic problems worldwide in obtaining the very large amounts of land required," says Louis Pitelka, an ecologist in EPRI's Environment Division. "In addition, you have to remember that to achieve long-term CO_2 removal, harvested wood products would have to be stored permanently to prevent decomposition. An alternative approach would be to use plants as a replacement for fossil fuels."

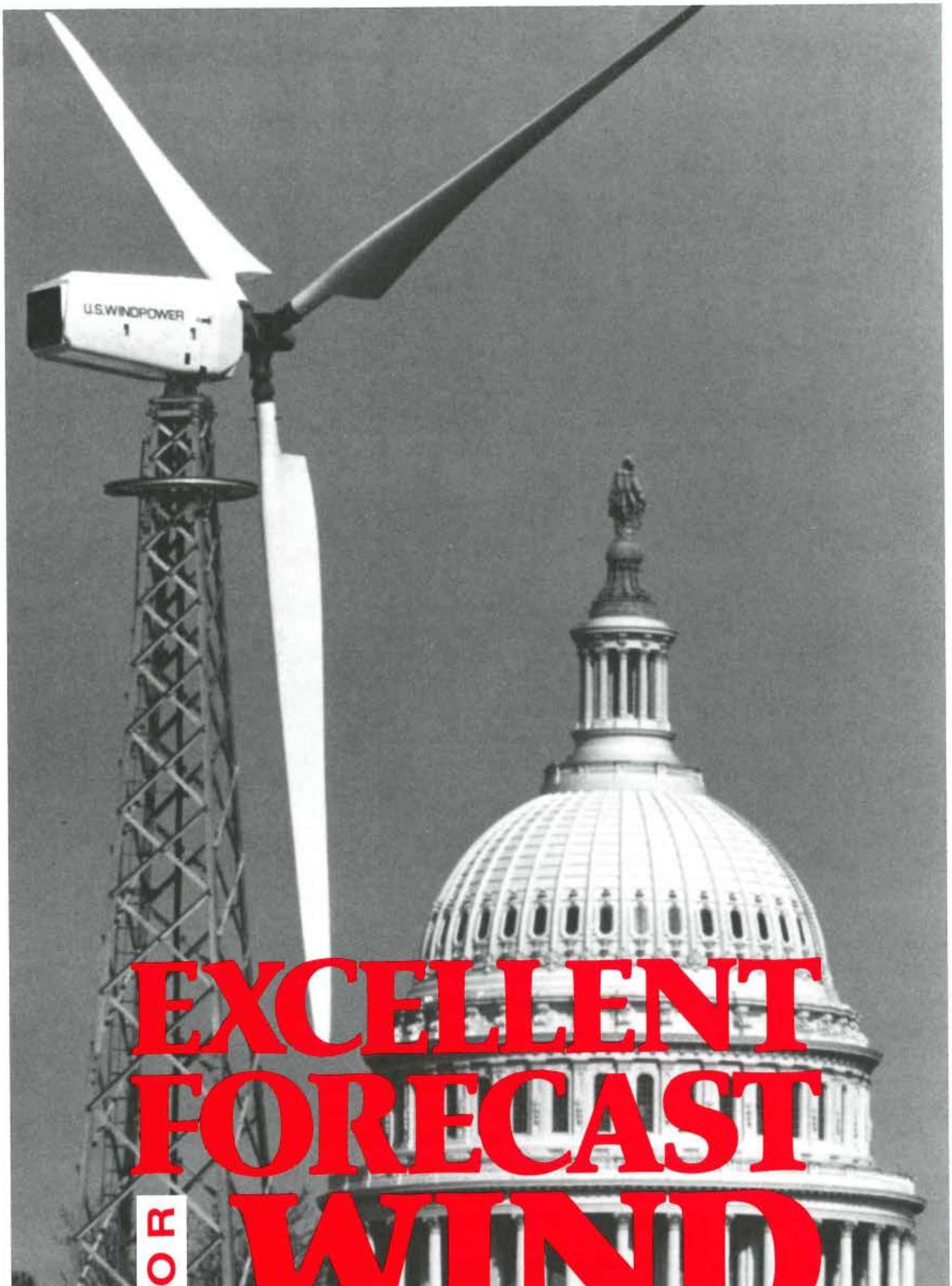
Contingency planning

While we are still far from a final solution to the greenhouse problem, the good news is that processes are being put in place to gain much useful knowledge. Any warming that does occur will help refine climate models. The influx of scientific talent and funding into greenhouse research, already under way, will help advance our understanding of possible climate changes. In addition, the payoff from R&D aimed at developing mitigation and adaptation measures is extremely high: EPRI analyses show that technological innovations could lower the cost of mitigating the greenhouse effect by perhaps trillions of dollars.

"The global climate problem will be with us for the next century at least. What we need is a better framework for conducting analyses and facilitating debate on appropriate policy responses," says Stephen Peck, director of the Environment Division. "A contingent decision-making framework would be appropriate—meaning one in which we make a set of decisions now, based on what we know, and then plan to improve on these decisions once more knowledge has been gained. EPRI could make a substantial contribution in this area, having had previous experience in developing integrated risk assessments and decision frameworks."

One additional advantage of this approach is that it helps identify, at each point of decision, the most important issues for further research. "This is a central concern in dealing with a problem as broad and complicated as global warming," Peck points out. "We can't pursue all possible avenues of research at once, however urgently answers may be needed. We're never going to have perfect knowledge on an issue like this. But if the research community chooses its work wisely and pursues it aggressively, we won't be making decisions in the dark." ■

This article was written by John Douglas, science writer. Technical background material was provided by Stephen Peck, Chuck Hakkarinen, Leonard Levin, and Lou Pitelka, Environment Division.


U.S. WINDPOWER
EXCELLENT
FORECAST
FOR
WIND

Last April in Washington, D.C., something unusual happened in the shadow of the Capitol on the Mall adjacent to the National Air and Space Museum. The occasion was an environmental-energy technology fair called Earthtech 90, held in connection with the 20th anniversary of Earth Day. As the capital press and dignitaries viewed live television pictures beamed from a California hillside, two U.S. senators and the deputy secretary of energy pushed a button that remotely turned on some 200 wind turbines, adding another 20 MW of power from a renewable energy source that now supplies over 1% of the Golden State's electricity.

Perched atop an 80-foot tower near the Washington gathering of VIPs was a 100-kW turbine just like those that had been activated over 2000 miles away in the Montezuma Hills near Suisun Bay, northeast of San Francisco. The machines, more than 3700 of which are operating in California, are the pride of U.S. Windpower, a leading manufacturer of wind turbines and the largest supplier of wind-generated electricity in the world.

The wind plant startup helped kick off the five-day Earthtech, featuring over 100 organizations with products and services for environmentally sustainable development. And it highlighted a growing recognition of wind energy as a proven, renewable, and nonpolluting energy resource that is becoming economically attractive for locations with good winds. After nearly a decade of deployment largely induced by generous tax credits and favorable, guaranteed energy prices, over 15,000 wind turbines have been installed in California, mostly in three high-wind areas, with an aggregate power rating of over 1500 MW. Some 23 MW of turbines in Hawaii also generate commercial power.

Wind power's image both benefited and suffered in the early 1980s. Each year, dozens of developers raced to install thousands of small (mostly 50–150 kW) wind turbines of American and European

THE STORY IN BRIEF

Wind energy is coming of age as a proven, nonpolluting renewable energy resource. Over the last decade, more than 16,000 wind turbines have been installed in California and Hawaii, with an aggregate power rating of over 1500 MW. Even more important, there is a growing recognition that wind energy may have application beyond these geographic regions. But competing internationally and developing a more extensive domestic market in utility-owned and -operated wind plants will require even more economical turbines than those running in California. With the maturing of the technology and a shakeout among manufacturers and developers in recent years, a handful of wind power firms are applying the best of what has been learned to design wind machines with truly superior performance. U.S. Windpower, with the support of EPRI and utilities, is developing such an advanced, utility-grade turbine for the 1990s.

manufacture in California to take advantage of annual tax credits. Financing for the independent power projects came from both Wall Street and Main Street.

"A lot of people thought the wind power industry would disappear once tax credits expired," recalls Edgar DeMeo, EPRI's program manager for solar power. But when the credits did run out in 1985 and 1986, he says, "hundreds of turbines continued to be installed, the cost of generating electricity grew more competitive with conventional resources, and as utilities noticed the successes, their interest in wind began to increase."

The basic principles of wind turbines, which combine rotors derived in part from helicopter technology with small induction generators, are fairly straightforward. Yet many early wind turbines were inadequately engineered and maintained and have not performed as well as expected. Many wind project developers are no longer in business.

Also in the 1980s, a federally sponsored technology development program that focused on large turbines with rotor diameters of up to 300 feet (compared with 30–60 feet for the smaller machines) wound down, with mixed results. Millions of dollars were spent exploring the promise of multimegawatt, utility-scale machines only to reveal their own special problems, including high cost, complexity, and lack of economic appeal to utilities in the face of deflated oil prices. Because wind power is a nondispatchable resource, its economics in California have been closely related to the cost of electricity generated from oil and gas, the fuels most often displaced by wind-generated kilowatthours.

Despite the negatives that gave wind energy a bad name in some quarters (some utilities, for example, were required to pay more than they wanted for wind-generated electricity they didn't always need), something positive was also happening for wind power. As manufacturers and wind plant developers moved up the learning curve, turbine and rotor technologies improved with better designs; wind plant economics improved with larger, higher-rated turbines, more sophisticated operation, and diligent maintenance; and utilities began to appreciate the strategic value of wind as a generating resource.

With the maturing of the technology and a shakeout among turbine makers and project developers in recent years, wind power today is a going business for a handful of firms. And they are beginning to look beyond the artificially stimulated market in California to much bigger and fully commercial markets in other parts of the United States and in Europe. Observers of the European scene project that 2000–4000 MW of wind turbines could be installed there in the 1990s.

But to compete internationally, as well as to crack a potential new U.S. market in utility-owned and -operated wind plants, will require even better, more economical turbines than the best of those running in California's high-wind passes, which produce electricity in some cases for under 7¢/kWh. Manufacturers in Europe, Japan, and the United States are already developing and testing advanced wind turbines. In part to ensure that such an economical machine will be available from a domestic manufacturer, EPRI and Pacific Gas and Electric, the nation's largest electric utility, have teamed up with U.S. Windpower, the only integrated American wind company, to develop an advanced, utility-grade turbine for the 1990s.

Learning the lessons of the 1980s

The rapid growth of installed wind power in California during the 1980s served in key respects as an accelerated period of research, development, and demonstration. In a relatively short time, it pushed wind technology from simple machines derived in part from irrigation-pumping generators to larger, high-power machines of several hundred kilowatts suitable for mass deployment in megawatt-scale wind plants, often known in the early 1980s as wind farms.

When the first turbines began to be deployed, the operating and maintenance costs, machine availabilities, capacity factors, and fatigue life of various models were largely unknown. And there were concerns, particularly among utilities with whose transmission systems the wind plants were to be interconnected, that the uncertain electrical behavior and interaction of large numbers of wind turbines might play havoc with the power grid.

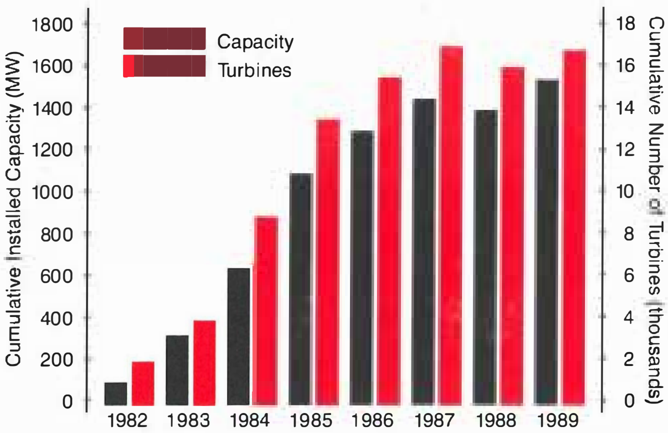
"We've had a heck of a research demonstration going on in our backyard in the Altamont Pass," observes Carl Weinberg, manager of research and development at Pacific Gas and Electric. The blustery region just east of the San Francisco Bay area boasts more wind turbines than anywhere else in the world, nearly half of the state's total.

Now a second large wind resource area in PG&E's territory is set for expanded development: Solano County's Suisun Bay region northeast of San Francisco, where U.S. Windpower's latest wind plant was installed and where PG&E formerly operated a large, 2.5-MW experimental turbine. Among the many insights PG&E has gained from its experience as both a turbine operator and a buyer of wind-generated electricity is that both the Altamont and Suisun Bay areas have seasonal wind energy profiles that fit well with demand for power on the utility system, Weinberg says. The utility demand peak is higher in the summer, when the wind blows stronger. Moreover, the daily wind power pattern at Suisun matches well with the utility's late-afternoon peak-demand period; the aggregate daily power curve from turbines in the Altamont Pass region, however, typically lags the utility system load peak by several hours.

"Of the various turbines in the Altamont, as in the other developed wind areas, there is a conglomerate of failures and successes," adds Weinberg. "But what has emerged from the Altamont is a proven concept for how to operate wind plants efficiently and economically. Having closely observed the performance of

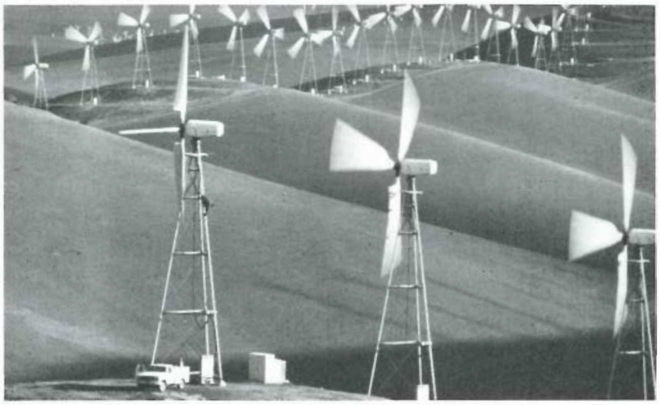
Wind Power's Growth Through the 1980s

U.S. installed generating capacity in wind turbines grew rapidly during the last decade, largely as a result of favorable tax credits and energy rates for independent power producers. Over 16,000 wind turbines with an aggregate power rating of over 1500 MW are now installed, nearly all in California but including some in Hawaii. Despite the expiration of federal and state tax credits in the mid-1980s, which slowed somewhat the rate of new installations in California, the number of operating turbines and the amount of cumulative capacity continue to grow. California's wind plants extend over more than 27,000 acres, yet only 10–15% of the area is actually occupied by the turbines. (Photos courtesy of American Wind Energy Association, Paul Gipe, SeaWest, U.S. Windpower, and Zond Systems.)



Micon turbines, San Gorgonio Pass

U.S. Windpower turbines, Altamont Pass



Mitsubishi turbines
at SeaWest Industries, Tehachapi Pass

Vestas turbines,
Zond Systems, Tehachapi Pass

Danwin turbines,
SeaWest Industries, Tehachapi Pass

U.S. Windpower: An Integrated Wind Energy Company

U.S. Windpower is unique as the only vertically integrated American wind energy firm. Turbines are manufactured at the company's Livermore, California, headquarters. Crews install and maintain the machines at carefully chosen sites in the nearby Altamont Pass and Suisun Bay wind regions. The output and operation of the company's 3700 installed turbines are monitored from a state-of-the-art computer-based control center. Continuing installation is expected to bring U.S. Windpower's aggregate installed turbine capacity to over 400 MW this year. In a cooperative effort with EPRI and utilities, U.S. Windpower is developing an advanced wind turbine for the 1990s that is expected to offer improved economics and power quality.

Wind plant control center

Maintenance training

Turbine manufacturing

Field maintenance

Operating wind plants

various machines and projects over the years, we view the California wind experience, on balance, as one of the alternative energy success stories of the 1980s."

As Weinberg and others who have tracked California's wind plants note, projects have recorded a wide range in key performance parameters, all of which affect whether a particular turbine makes money for its owners without tax credits.

Capital costs of turbines installed in 1988 and 1989 were down to $1000–1100/kW; some machines installed earlier cost several times as much. Operating and maintenance costs run 1–2¢/kWh; at some of the best-managed wind plants, they have stabilized around 1.4¢/kWh, according to Robert Lynette, a consultant to EPRI who has gathered and analyzed an extensive base of performance statistics on many of the wind plants. Availability factors at wind power stations range from 44% to as high as 98%, with many plants routinely achieving better than 90% as a result of effective maintenance programs.

When the industry began, it was basically unknown what sort of capacity factor a well-run wind plant might achieve. Capacity factor is a key variable affecting the cost of energy from a wind turbine; the greater the fraction of time a turbine is generating, the more energy it produces and the lower the cost of each kilowatthour generated. In the early 1980s, wind plant capacity factors ran below 15%. Now the best stations manage 35%, as capacity factor is traditionally defined. Given that the wind does not blow all the time, this level of performance is near the maximum possible with the California wind resource. "Some of the best wind plants today, using state-of-the-art turbines, are generating well over 90% of the energy they could produce with perfect operation," says EPRI's DeMeo.

On the other hand, many turbines have not generated nearly as much energy as developers anticipated. This has partly been the result of poor siting or inadequate assessment of the wind resource. Developers have since learned the importance of extensive wind speed measurements at specific locations and heights and the large effect that siting errors of as little as 10 feet can have on energy production (a loss of 10% or more).

Moreover, wake effects (in which some turbines in closely spaced wind plants blunt the wind reaching machines behind them) can reduce capacity factors by over 50%. "This has been particularly true of some wind plants in the San Gorgonio Pass area east of Los Angeles, where turbines are typically arranged in fairly close rows along flat terrain," notes John Schaefer, an EPRI project manager in the Generation and Storage Division. "Turbines in the Altamont, where wind speeds are somewhat lower, generally have slightly lower capacity factors; but because they are sited more along ridge lines and rolling hills, they have suffered far less from wake effects."

Turbine component fatigue life was another key uncertainty when wind plants first came on the scene. Most turbines were intended to last 20–30 years. But there are considerable dynamic fatigue and cyclic stresses on an elevated steel structure and machine with a rotating airfoil that must endure buffeting winds day in and day out, and early on these could be designed for only on the basis of estimates. Also, the constant rotor speed at which most turbines are designed to run means not only that proportionally less energy is captured at higher wind speeds, but that the greater fatigue stresses at higher winds are transmitted directly to the turbine and its structure.

By 1987 availability factors at many wind plants began to dip, as the effect of fatigue failure on the earliest installed machines became apparent. Many components simply wore out or came apart. Many turbines were replaced, and some were left to rust. Blades were a problem as well. Poor design and quality control in manufacturing led to blade root failure in some cases. In others, blade soiling from the buildup of insect debris impaired aerodynamic efficiency to the point that energy production typically dropped as much as 15%; for one turbine model, the drop was as much as 50%. Many turbine blades are now regularly scrubbed, and new designs are being developed that operate more efficiently with rough surfaces.

According to Lynette, most of the uncertainty about turbine fatigue and blade life has been resolved and corrected in the latest designs. "We can say much more confidently now that with intelligent maintenance programs, turbines should last at least 15–20 years," he says. "Not all the manufacturers are there yet, but enough technical data and understanding of design and fatigue characteristics are available that there are really no show-stoppers." (U.S. Windpower asserts that with normal replacement of moving parts, present turbines should last 25–30 years.)

Lynette notes that as manufacturers strive to lower installed turbine costs still further—moving toward $600/kW by the mid-1990s—by reducing weight and complexity, the challenge will be to maintain adequate fatigue life. This may be particularly true for the already comparatively lighter and more-economical American-made turbines; the European models—such as those of Danish origin, thousands of which are installed in California—are typically bigger, heavier, and more expensive.

The electrical aspects of interconnecting wind plants to utility transmission systems have been far less problematic than some people feared in the early days, although this is largely because nearly all wind power in California is supplied to the state's two largest utilities. Their large, diverse power systems are more able to accommodate substantial increments of power rising and diminishing with the wind than are less-extensive utility systems that have more-constrained transmission capacity and in which wind plants like the ones in California would represent a much larger fraction of total generation.

But even in California, transmission capacity limitations near the wind regions have sometimes constrained project development. And given the high cost and many obstacles that face any effort to site and build new transmission lines almost anywhere in the United States today, transmission potentially could pose a significant limit to wind power development.

Initially, it was feared that the induction-type generators used in virtually all of today's wind turbines would cause voltage control problems because they would draw large amounts of reactive power from the utility grid, dragging down voltage levels and choking a transmission line's current-carrying capacity. That has been largely eliminated by equipping the wind plant power collection systems with capacitors that compensate for their reactive power consumption. But a large amount of wind capacity feeding the remote end of a long transmission line can still cause voltage control problems.

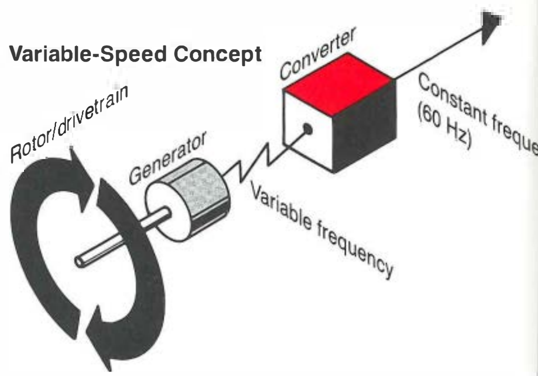
Both to improve operating economics by capturing more energy and to reduce dynamic fatigue stresses, a few wind turbines over the years have been designed for variable-speed operation. Experimental machines built under the federal wind program helped pioneer the concept. In early variable-speed machines, cycloconverters or rotor-slip energy recovery systems enabled the turbine rotor to operate at variable speed as the wind speed changed, thus capturing more of the available energy while maintaining a constant-frequency, 60-Hz electrical output.

But the electronics used in most early variable-speed machines can create another problem. They can inject significant amounts of harmonic current onto the utility line, affecting customer loads nearby and posing a damaging overload potential as a result of harmonic resonance within the utility system.

Advantages of a Variable-Speed Wind Turbine

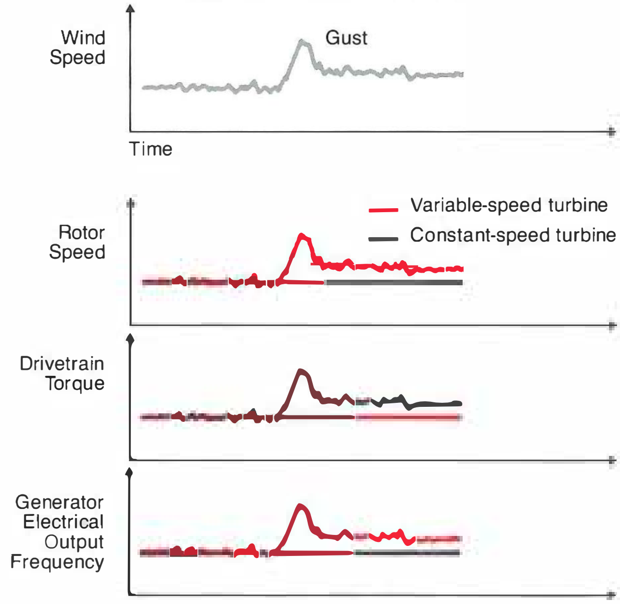
Conventional wind turbines are designed to operate over a very narrow speed range in order to maintain a constant-frequency power output to the grid. Wind gusts or speeds higher than the design speed increase the torsional stresses on the drivetrain. An advanced, variable-speed turbine being developed by U.S. Windpower with utility industry support employs a power electronic converter between the generator and the utility line. This allows the rotor and the generator to speed up with gusting or stronger winds. The increased rotational energy is then converted into more electricity without increasing torque on the drivetrain. The converter maintains a constant-frequency line output despite the generator's variable output frequency.

Variable-Speed Concept



Advanced turbine prototype

Responses to Changing Winds



A role for an advanced wind turbine

By late 1986, the year that state tax credits for California wind projects expired (the federal tax subsidy ran out a year earlier), it was becoming apparent to various players and analysts of the burgeoning wind power industry that the turbine technology deployed up to that point probably could not sustain the business for long.

True, many machines and even projects were profitable under utility purchase contracts whose energy prices were set in 1983. But with the collapse of oil prices in the mid-1980s, new contract energy rates became much less attractive. Even for projects in California's main wind regions, maintaining or enlarging profits meant developers would have to hammer hardware and operating costs down still further or come up with more-productive, better-performing turbines.

It was also becoming clear that the challenge was even more pronounced if wind developers were to expand beyond California's high-wind regions, where winds average 15–20 mph, into regions with somewhat less energetic winds—with average speeds of, say, 12–14 mph—which include vast areas of the Great Plains, the Northwest, even some of the higher ridges of the Rocky Mountains in the West and the Appalachian Mountains in the East. Because the power available from the wind increases proportionally with the cube of the wind speed, even small differences in speed can mean substantial differences in the amount of energy produced, other things being equal. (There are also many areas with winds as good as or even better than California's, where more-severe conditions would require turbines with much greater durability.) Moreover, in most of the country beyond California, wind-generated electricity must compete not with oil-fired electricity but with lower-cost coal-fired electricity.

Also in the 1980s, a handful of utilities were showing a budding interest in wind energy as a potentially viable future resource option for their own investment. Their interest was motivated less by the cost of electricity from then-current turbines than by the wind's strategic potential value as a fuel displacer (and a hedge against future fuel price rises) that entails zero pollutant emissions. This upturn in utility interest was reflected in the participation of nine utilities with EPRI and the Department of Energy in the formation last year of a wind energy interest group.

Against the backdrop of a brightening utility outlook on wind energy's long-term prospects—and encouraged by the realization that relatively modest enhancements could move wind turbines squarely into the realm of economically attractive electricity generation costs—EPRI organized and cosponsored with U.S. Windpower an advanced-turbine feasibility study in 1987. Three utilities (PG&E, Virginia Power, and the Bonneville Power Administration) participated in technical reviews of the work. The basic question was whether a state-of-the-art utility-class wind turbine could be produced that incorporates power electronic control for improved energy capture and power quality and that generates electricity for 5¢/kWh or less.

After a year's effort, U.S. Windpower concluded that such a goal was indeed achievable. Within a short time, EPRI was helping to organize a consortium for a five-year program headed by U.S. Windpower that would develop and commercially manufacture such turbines for both domestic and international markets. The $20 million program is primarily funded by U.S. Windpower. PG&E is participating in the effort, and other utility cosponsors are anticipated. The turbine consortium is unusual for EPRI in that the Institute and the utility cosponsors will share in a percentage of the revenues from future commercial sales.

The development target is a variable-speed machine that employs advanced electronic control, in part scaled up from adjustable-speed motor drive technology. As noted earlier, today's constant-speed turbines are optimized for energy capture for a given rotor length at a particular speed in the wind power curve; wind speeds above that point result in less-than-optimal energy capture and transmit more dynamic loading to the structure. In contrast, a variable-speed machine's rotor will speed up with higher winds, providing a torque-limited, mechanically softer drivetrain.

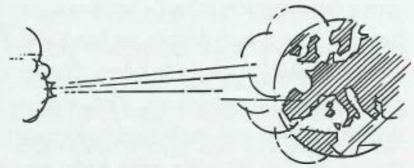
The variable-speed turbine's somewhat larger wind-speed operating envelope is expected to improve energy capture by 10% or more and to result in reduced dynamic stresses. And because the turbine's drive shaft can speed up with higher winds, storing some of the additional energy as kinetic energy, the design also permits a higher power rating for a given rotor length.

The main features of the advanced turbine were chosen on the basis of the technical feasibility studies as well as on U.S. Windpower's large base of experience with its workhorse 56-100 model, a 100-kW, third-generation evolution of the basic turbine it has manufactured since it entered the wind business. A technical review committee made up of EPRI, PG&E, and DOE representatives and other technical experts has provided input to the design and is closely monitoring the machine's development and fabrication.

At 54 feet long each, the advanced turbine's three blades will sweep an area over three times the area swept by the 100-kW model's 28-foot-long blades. The new rotor length was chosen because it has the lowest projected capital cost per kilowatthour generated. Like its predecessor, the rotor will be variable pitch and made of fiber composite; unlike the earlier model, the new rotor faces upwind. The advanced machine will have three times the power rating—300 kW. It features a parallel-shaft transmission with dual generator output shafts. The tower, like those used for the 100-kW model, is an open-truss type.

As mentioned, variable speed is not an

Winds of Change Blowing in Europe



Many observers believe that the next large stage for substantial growth in wind generating capacity may be in Europe, where development efforts have lagged those in the United States by several years. This has been the case despite a proliferation of European-based wind turbine manufacturers in the 1980s, largely to supply machines to the rapidly expanding independent power market in California. Most of these companies were aided by government financing subsidies and export assistance. Following a recent round of mergers and consolidations, several companies remain as potentially strong competitors in international markets.

As EPRI consultants found last year when they visited and interviewed many of the European organizations involved in wind energy, Europe's somewhat more recent blossoming of wind power development has allowed many programs to learn the lessons, and avoid some of the pitfalls, of the U.S. experience. For example, one notable contrast for wind development in Europe is that programs have been much more cooperatively organized and have directly involved utilities (some of which appear to have a strong interest in wind) with manufacturers and government agencies.

There are active wind development and demonstration programs in nearly every country in Western Europe as well as under the auspices of the Commission of the European Communities, the umbrella organization that is bringing about the integration of a true European common market, set for 1992. Some 200 MW of wind turbine capacity have already been installed in Denmark; several tens of megawatts are operating in Germany; and other countries, including Britain and the Netherlands, also count installed capacity in the megawatts.

Official projections of wind capacity planned for installation in Western Europe through the 1990s add up to some 4000 MW—nearly three times California's present installed capacity. Some observers believe that a more realistic figure is about half that amount, which is still more than has been placed in operation in California over a similar period of time.

Several European countries, including Denmark, Germany, and the Netherlands, have had significant government subsidy programs for wind energy systems. Both land-based and offshore installations are being planned under these programs. Unlike the U.S. approach, most of the subsidies are tied directly to kilowatthour production, rewarding actual electricity generation. Moreover, incentives are available to utilities as well as to third-party developers. Overall government funding for wind turbine technology development in Europe is estimated to be at least 10 times that of the declining government-funded research in the United States ($80 million compared with $8 million).

Many of the European government programs are stressing large, multimegawatt wind turbines, as did the federal program in this country, rather than the smaller machines that have dominated in California. And in addition to multiturbine wind power plants interconnected to utility systems, as found in the United States, another application of wind turbines is being explored in some European countries—namely, their use with diesel generators in a hybrid arrangement for geographically remote, electrically isolated power systems. □

entirely new wrinkle for wind turbines. But most earlier, experimental variable-speed machines employed fairly crude electronics that could add substantial harmonic currents to the line output. The advanced U.S. Windpower turbine's power electronic controller initially is being developed around a power Darlington transistor, essentially a high-power, high-frequency on-off switch. The transistor-based converters will rectify the generator's variable-frequency ac to dc and then invert it back into relatively harmonic-free, constant-frequency (60-Hz) ac for relay to a step-up transformer and supply to the utility grid.

In addition to softening the drivetrain through variable-speed operation of the generator, the electronic controller will permit the turbine to be set to consume reactive power from the utility system or to supply it to the system, depending on the need, or to operate at unity power factor (in which reactive power is neither added to nor taken from the grid). It is this variable-speed, power electronic feature that will give the advanced turbine what experts call utility-grade power quality and will transform the turbine from a potential system interconnection worry for utilities to a more valuable addition to the system.

Notes J. Charles Smith, a vice president of Electrotek Concepts and a consultant to EPRI on the project, "The machine really has the potential be a good neighbor on the power grid. Even when the wind is not blowing and the turbine is idle, the power electronics could be switched onto the utility line to provide reactive power support for voltage control. That means the turbine could have operational value to a utility beyond its actual kilowatthour production."

Smith says that as the cost of advanced electronics continues to drop and reliability improves, the Darlington transistor at the heart of the controller now under development could give way to higher-power, higher-speed insulated-gate bipolar transistors. Eventually, the goal is to use metal oxide–controlled thyristors. Such so-called smart power modules potentially could also feature self-checking diagnostic controls and error correction.

Functional electronic converters have already been tested, and versions with advanced components are now being developed by U.S. Windpower, along with the rest of the advanced turbine, at the company's Livermore, California, headquarters at the edge of the windswept Altamont Pass. As part of the first phase of the overall project, a constant-speed prototype of the advanced turbine, without electronic drive controls, was built and installed in the area in 1989.

Nearing the commercial market

Development work, including dynamic mechanical and structural testing, continues on the constant-speed version of the advanced turbine, designated by U.S. Windpower as model 33-300. The first variable-speed prototype may be built and start to undergo testing in California by the end of this year. During 1991 U.S. Windpower plans to build as many as 50 prototypes, some constant speed and some variable speed, for extensive side-by-side performance testing at several wind resource locations. Utility participants are also expected to test variable-speed prototypes through the end of the development program in 1993.

Around then, after the insights from testing are fully incorporated and the machine is fine-tuned, U.S. Windpower expects to launch commercial production of the 33-300 turbine, both for its own development projects and for sale to utilities and other wind project developers worldwide. "We're in the wind power plant business, and we intend to be a premier world-class supplier of wind plants to the utility and independent power industries," says Dale Osborn, the company's president.

U.S. Windpower is a subsidiary of the privately held Kenetech Corp., major shareholders in which include Allstate Insurance Co. and two investment firms—Pittsburgh's Hillman Co. and Chicago's F. H. Prince and Co. (Half a dozen major U.S. utilities, meanwhile, are equity investors in various U.S. Windpower projects.)

"This new, large, utility-scale wind turbine is the key element of our business strategy for the future," adds Osborn. "If we can achieve the technical and financial goals of this project, we will define a completely new market for wind power—a market in which it will be commercially viable generation on the basis of fuel savings alone. I believe this new turbine will be the key innovation that changes the wind industry from a push market that has largely depended on subsidies or environmental considerations to a pull market in which wind energy is fully economical at today's cost of energy from fossil fuels."

Osborn believes that the variable-speed turbine, coupled with even more sophisticated programmable software than controls today's machines, will offer such an improved utility electrical interface that dramatically greater amounts of wind capacity can be accommodated on a typical utility system than is currently possible without threatening power disturbances. "Conservatively, it will double the potential utility market," he predicts, which, on the basis of the national wind resource, is many thousands of megawatts.

From his career background in electronics, manufacturing management, and marketing, Osborn confidently predicts that the advanced turbine "is going to be a real economic head-knocker. We're talking about a potential 20–30% reduction in the delivered cost of energy, and I am prepared today to sign all the utility power purchase agreements I can get for 5¢/kWh. We're striving right now for a 5¢/kWh machine, but a 3¢/kWh turbine is not out of reach."

Observes Jim Birk, director of EPRI's Storage and Renewables Department, "When the cost of wind generation reaches the levels U.S. Windpower is going for, wind will represent one of the lowest-cost sources of electricity for a utility with good resources." Birk urges utilities that want to take advantage of the opportunities in wind power to begin assessing the local wind resource now and to tap into the extensive operating experience base EPRI has documented.

Achieving such low delivered-energy costs may be critical to the survival of a domestic turbine-manufacturing and wind power industry, for U.S. Windpower's Osborn knows well how the forces of international competition are lining up across both the Atlantic and the Pacific. Wind turbine makers in Austria, Belgium, Britain, Denmark, Germany, Italy, Japan, and the Netherlands have already produced or are known to be developing new turbines, some with electronic controls similar to the approach in the U.S. Windpower machine.

In addition to those turbine manufacturers already pursuing advanced machines, a powerful potential competitor is now moving up the learning curve (traveled some years ago by U.S. Windpower) with a constant-speed turbine that has already become the preferred unit of one of California's three large wind plant developers. The giant Mitsubishi Heavy Industries has sold 660 of its 250-kW turbines to SeaWest, a San Diego–based company that operates wind plants in the Altamont, San Gorgonio, and Tehachapi passes. The MHI turbines are said to be priced below any other comparable machine, with a 10-year warranty. Observers believe MHI could develop and field a variable-speed machine within a short time if it chooses to do so.

"There is no American machine made today that I would consider buying," says Charles Davenport, SeaWest's chairman and CEO. "If all else were equal, I'd buy American, but they're not all equal. I hope someday U.S. Windpower or somebody will produce a machine that competes with Mitsubishi's, but it will take matching credit support and service, not just a good turbine."

Osborn says he welcomes MHI's entry into the world wind turbine market "because it reinforces my vision that this industry really hasn't started yet. But I assure you Mitsubishi is scratching its collective head today over engineering problems we solved in 1984. Also, with over 38 million turbine operating hours, U.S. Windpower has the most experience in properly operating and maintaining wind turbines.

"As far as the American market goes, I believe we're several years further up the learning curve and have a substantial competitive advantage as a U.S. marketer. Our 56-100 machine is the only wind turbine in the world that can be financed solely on its track record," Osborn adds. "And we continue to believe the United States is the biggest potential wind energy market in the world."

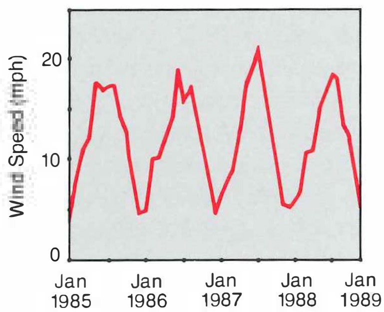
Meanwhile, U.S. Windpower is forming joint ventures with partners in Japan and Europe, where it also expects its advanced turbine will be competitive. Osborn says the company hopes to have as much as 1 MW of turbine capacity running on Okinawa within the next year under a joint marketing effort with Toyo Engineering. And U.S. Windpower has secured a beachhead in Europe via a manufacturing joint venture with Spain's Abengoa to initially supply 15 MW of wind plant capacity in that country. Such alliances are considered essential for American manufacturers of all sorts of products as the 1992 integration of Western European markets into a true common market nears.

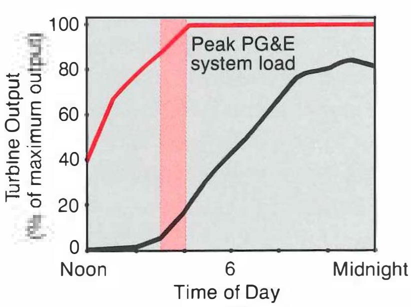
U.S. Windpower also has a joint venture in Britain with the Wind Energy Group (itself a British joint venture) and operates over 20 WEG turbines in the Altamont. "We're not going to be preempted from doing business in Europe," says Osborn. "But we probably will be at a significant disadvantage if we do not have at least 75% European manufacturing content. So we're pursuing those arrangements now, but we also believe that if such a trade restriction applies in Europe, the same should apply here."

Still, he continues, the big market is here at home. "What we're doing with this large-scale utility turbine gives me a solid basis for envisioning 1000-MW wind power plants in several areas of the United States where today economic development and jobs are sorely needed. There is really nowhere else in the world where you can think about projects on that scale. We believe the ultimate customer for our product, whether it's wind-generated electricity or a wind power plant, is the American utility industry. That's why the relationship we have with EPRI and PG&E is so important to us. We intend to design and produce a product that most fits the needs of utilities, so we felt it was critical to get involved with the best utility technologists we could find."

California's Altamont and Suisun Winds: Variations on a Breeze

Two important factors influencing wind energy economics are the wind resource's seasonal and daily variability. In two northern California wind regions—the Altamont Pass and Suisun Bay areas, where wind turbines are operating in Pacific Gas and Electric's service territory—the wind is strongest during the summer months, which is also when demand for power on the PG&E system is greatest.





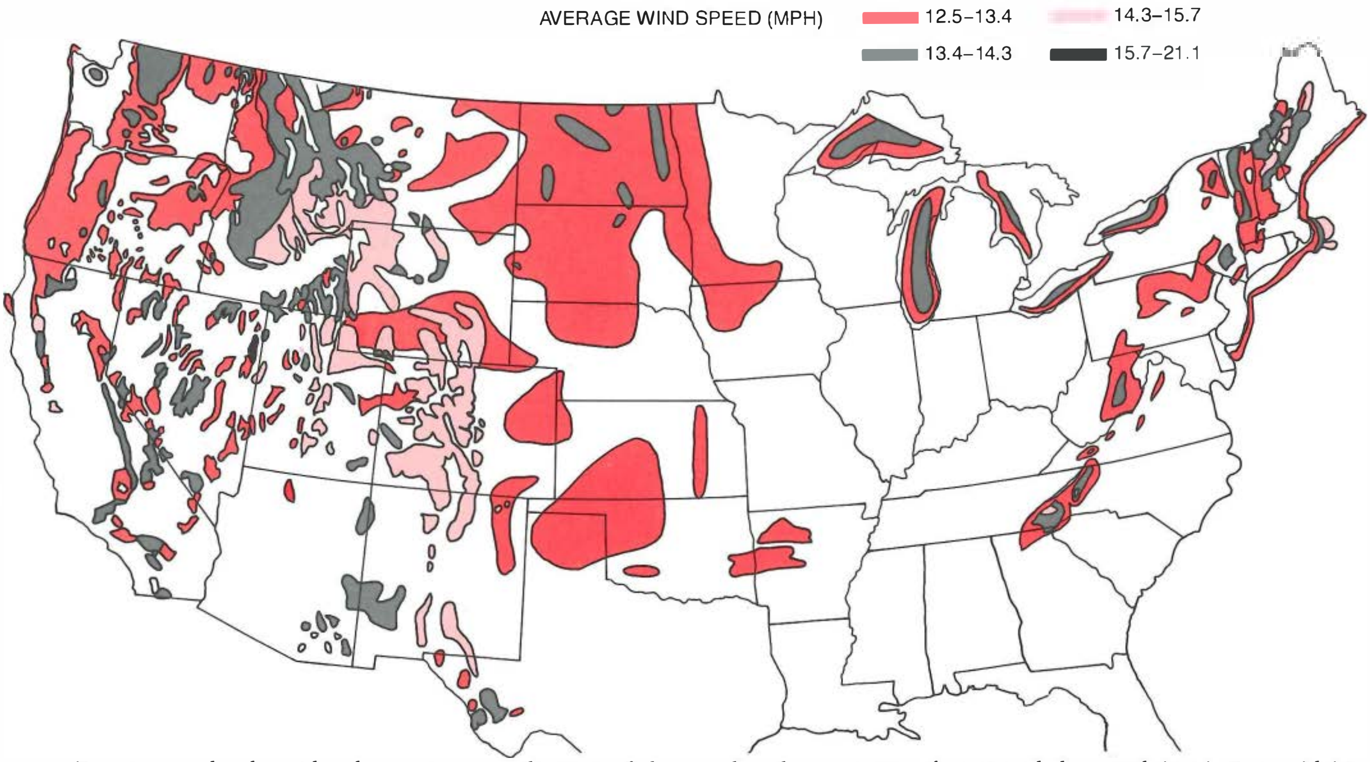
The Altamont and Suisun areas are less alike in their daily patterns of wind energy, however. Ideally, the wind plants would be generating at maximum output during the period of peak demand on the utility system. Plots of sample power curves for two turbines in 1988 show that the Suisun Bay site's output (color) fitted well with the typical 3–4 p.m. summer peak load on PG&E's system. Winds blowing through the Altamont Pass (black), on the other hand, generally pick up later in the day; maximum output of the turbine sited there lagged the utility system peak by several hours.

A chorus of approval

Observers of the EPRI–utility–U.S. Windpower advanced-turbine development effort seem unanimous in applauding the

America's Wind Power Resource: Large and Diverse

A map adapted from a wind energy atlas prepared by the Pacific Northwest Laboratory for the Department of Energy indicates annual average wind power in several classes of speed and energy density for the 48 contiguous states. Virtually all the wind generating capacity currently installed in the United States is located in three relatively small areas in California and on two of the Hawaiian Islands.



commitment to technology development and the utility interest in wind power that the project implies. "We're bullish on variable-speed technology for wind turbines," says Robert Thresher, manager of the wind research branch at the federal Solar Energy Research Institute. "But the nemesis of applying variable speed at larger machine sizes is how much it adds to the cost. That's where the U.S. Windpower program is pushing the frontier forward. They're trying to bring the advantages of variable speed to a turbine size and architecture that really has the potential to be cost-effective." Thresher and DOE officials say SERI is planning research activity to support variable-speed technology, including fundamental physics research and the development of improved computer codes for design analysis.

Eventually, notes Leonard Rogers, former director of the wind and ocean energy technologies division at DOE, the government hopes to initiate its own design work for an advanced variable-speed turbine that will integrate all of the engineering lessons learned in the 1980s. "The U.S. Windpower program is very encouraging to us because with EPRI and utility participation it indicates there is certainly a place for wind in the generation mix. Success of the joint effort will permit this renewable resource option to be further deployed a lot sooner than if the participants hadn't gotten together as they have."

The president of a utility subsidiary that already has experience operating a variable-speed wind turbine—the massive 3.2-MW MOD-5B funded by DOE and operated by Hawaiian Electric Renewable Systems on the island of Oahu—says that variable speed is definitely the way of the future and that applying it to a midsize turbine is the right move. "If U.S. Windpower succeeds with its program objectives, it ought to have a real world-class wind turbine on its hands," says Al Manning, president of HERS, a subsidiary of Hawaiian Electric Industries. "I'm anxiously awaiting the results." ■

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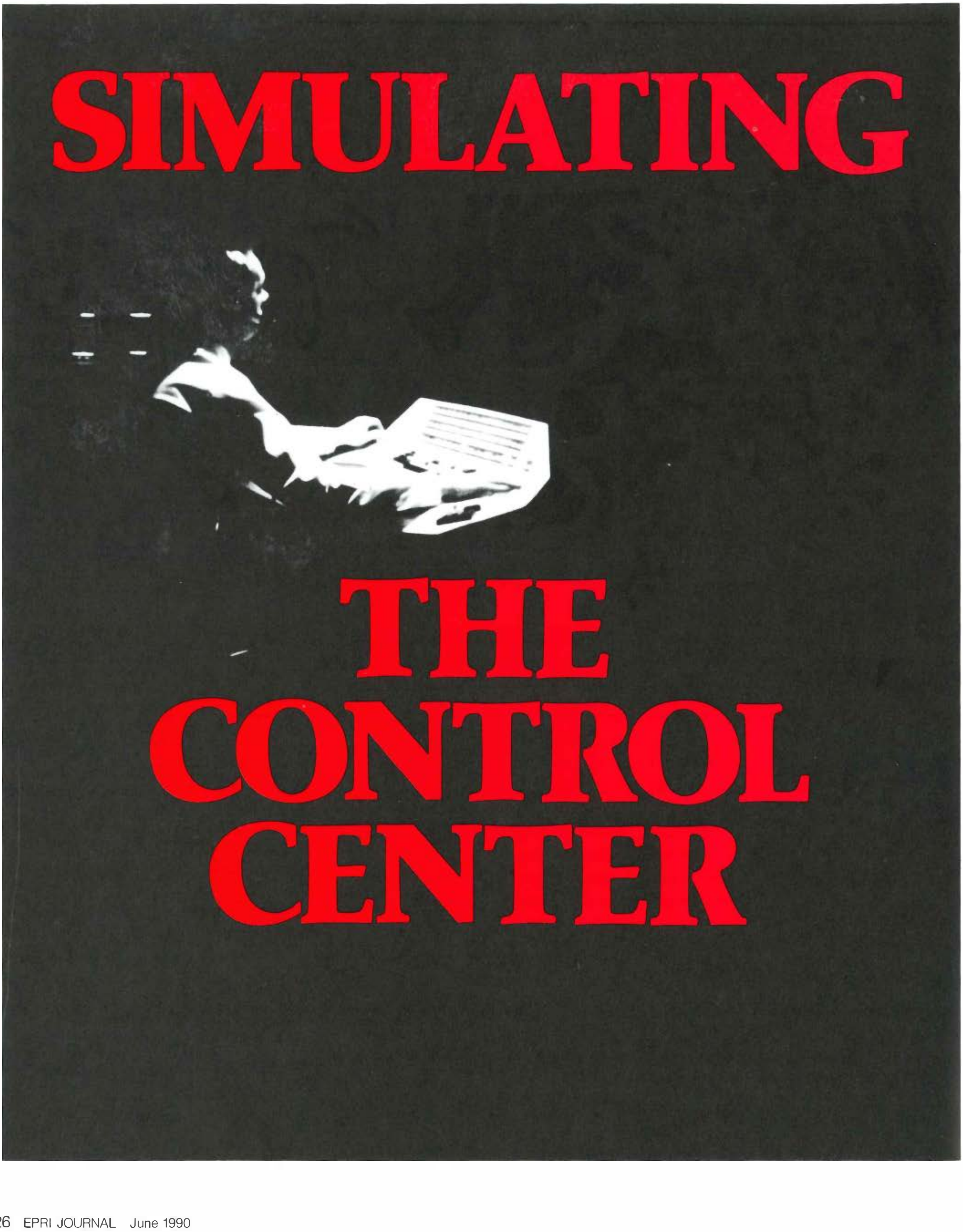
This article was written by Taylor Moore. Background information was provided by Edgar DeMeo and John Schaefer, Generation and Storage Division.

SIMULATING THE CONTROL CENTER



Working in shifts around the clock in control centers across the country, members of an elite corps of utility personnel preside over the operation of the most complex machine ever built—the national electric power system. Each of the more than 200 energy control centers in the United States serves as the brain for a portion of the vast interlocking network of generators and transmission lines that delivers power on demand to every sector of a society that runs on electricity. Each control center operator, or dispatcher, has to keep his or her part of the power machine running safely, reliably, and economically.

Power system control is semiautomatic, with much of the work handled by a computerized energy management system (EMS) that is continuously fed data from thousands of sensors installed in equipment throughout a utility's service area. The EMS monitors the state of the power system and performs the chores of matching generation to load and determining the most economical mix of generating units. But the ultimate responsibility for the smooth working of the power machine falls not to computers but to people. The control center dispatchers make decisions and take actions that computers cannot.

The vast majority of the time, the power system functions normally and the dispatcher is not overly active, just as an airline pilot isn't very busy when a flight is on course and all aircraft systems are functioning normally. But when normal operations are disrupted—because of a generator or transmission line outage, for example—the operator has to switch from being not so busy to being active. It's under these conditions that experience and skill pay off. Under acute time pressure, a bewildering array of data must be sorted through to obtain the information vital to understanding the situation; decisions must be made and actions taken to prevent the situation from worsening and then to restore things

THE STORY IN BRIEF

Utility control center operators, or dispatchers, play a critical role in keeping the nation's power systems running reliably and economically. As power systems have grown more complex and are operated closer to their limits, the dispatcher's job has become more challenging, underscoring the need for more-effective training than the on-the-job instruction they've traditionally received. Training simulators, analogous to those used to instruct pilots, can both accelerate the acquisition of experience needed to deal with power system emergencies and hone basic skills that pay off in improved economy during normal operation. Unlike early units, which were slow and had limited modeling capability, an advanced operator training simulator developed under EPRI sponsorship is so realistic that trainees can't distinguish between operating it and operating the actual power system. The simulator is being demonstrated at Philadelphia Electric and is ready for commercialization.

to normal. The dispatcher's job, like the pilot's, affords little margin for error.

"The dispatchers are a key line of defense against any events that may jeopardize normal, steady power system operation," says David Curtice, project manager in the Power System Planning and Operations Program. "They are the focal points for control of the system and are all-important to its health and success."

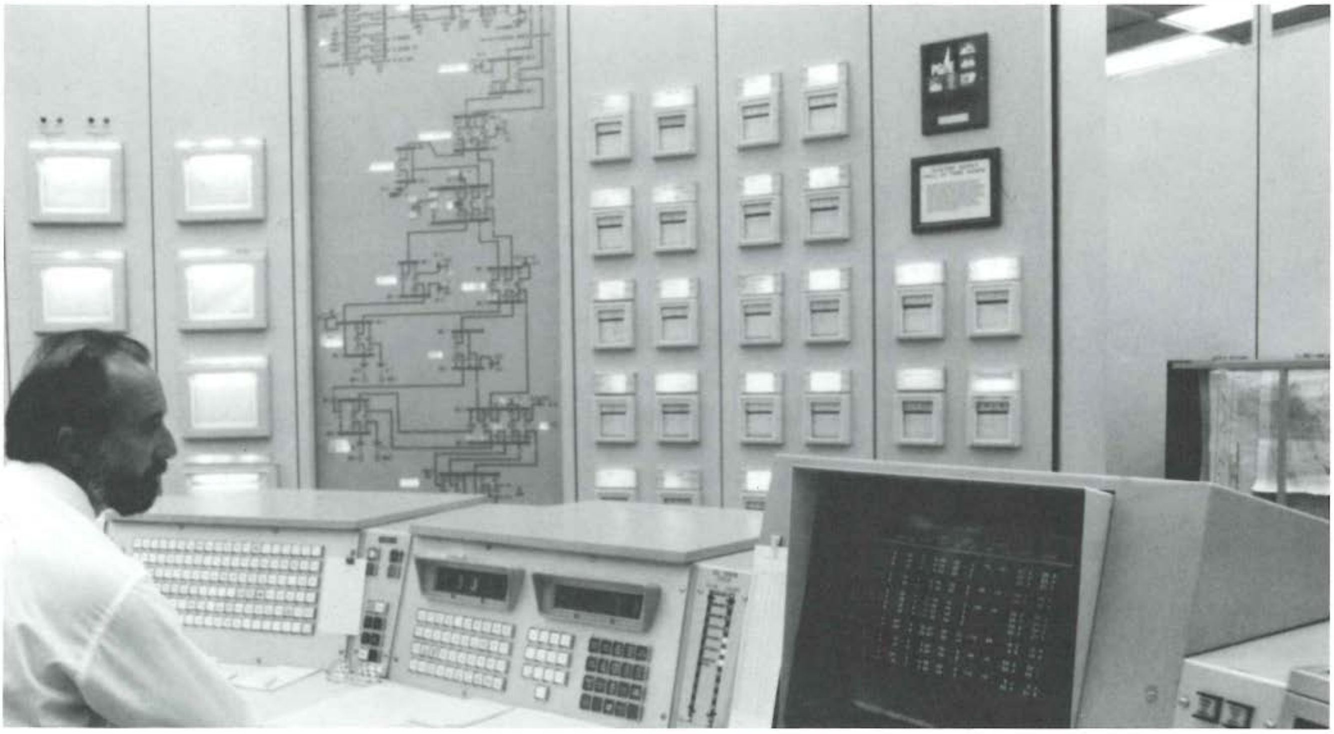
Most of the dispatchers working today acquired their skills slowly—through classroom study and, primarily, during on-the-job training under the wing of an experienced operator. Since actual emergencies are quite rare, most of the experience gained in on-the-job training involves normal operating conditions. To acquire the skills needed for handling emergencies or for restoring the power system after a blackout or partial blackout, the trainee has had to assimilate the hard-earned experience of seasoned dispatchers through descriptions or reports. This type of training just isn't sufficient to prepare prospective dispatchers for the full range of conditions that can occur during a major disturbance to the power system. According to a working group from the Institute of Electrical and Electronics Engineers (IEEE), approximately 90% of the problems that have caused emergency, near-blackout, or blackout conditions were problems that the operator had never encountered before.

The situation has been changing in recent years, however. Simulators, long used to train pilots, promise to dramatically change the way energy control center operators are trained. A computerized simulator that realistically models the behavior of an entire power system can present conditions rarely encountered during actual operation, allowing trainees to acquire years of operating experience in a short time without affecting customer service or damaging equipment.

EPRI has sponsored the development of an advanced control center operator training simulator (OTS) that can represent with high fidelity both the power

Managing a Power System

Energy control center operators schedule and coordinate virtually all the electric power flowing in the U.S. bulk power system. With the aid of computers and automatic control equipment, operators perform three broad functions: they dispatch generation to match the fluctuating customer load, schedule power interchanges with neighboring utilities, and monitor the security of the power system—that is, its ability to withstand sudden disturbances like short circuits or the unanticipated loss of system components. Power systems are designed to operate normally with some equipment outages, but major disturbances may cause multiple outages, triggering large and often sudden changes in voltage, frequency, and flows that can't be absorbed by the system. During these rare events the dispatcher must quickly recognize and understand the situation, make decisions, and take corrective action.



system and the control center of any utility. The OTS uses sophisticated software and an innovative computer architecture to produce, for the first time, a power system simulation and training environment so realistic that a trainee can't tell the difference between the simulation and the real thing. In development for the better part of a decade by Control Data Corp., the system is being demonstrated at Philadelphia Electric and is ready for commercialization.

"By simulating a wide variety of conditions, the OTS will accelerate the acquisition of operating experience," says Curtice. "Simulator training can help dispatchers develop the skills they need to deal with actual emergencies as well as to improve the economy and security of the power system during normal operating conditions."

Deluged with data

The need for such an advanced training simulator is becoming more urgent because the dispatcher's job is becoming more challenging—and critical—as power systems grow increasingly complex and control center equipment more sophisticated. The dispatcher today has more real-time data to sort through, more variables to contend with in making decisions, and more possible courses of corrective action to take in the event of a system disturbance.

The increased complexity is in part due to the interconnections between individual power systems. These allow bulk power transfers between neighboring utilities but also add to the deluge of data that the operator must keep track of and respond to. Whereas the dispatcher of the past controlled only the power supply to his utility's service area, perhaps several cities or part of a state, today's control center operator may be responsible for controlling the power flow to a region containing several states. As a result, the operator must keep track of not only his own power system but also those of neighboring utilities. In addition, independent power producers—nonutility businesses operating combustion turbines, small hydro units, and other generating technologies—are putting power on the grid that the dispatcher has to balance against his own utility's generation.

Of all the trends contributing to the dispatcher's burden, perhaps the most significant is the lack of new generating capacity, according to Neal Balu, manager of the Power System Planning and Operations Program. "Because we're not adding enough new generation to reinforce the system, existing transmission facilities are getting stressed—loaded up near their limits," he says. "And as the power system is pushed closer to its limits, the consequences of incorrect operation become more serious." Preserving power system security in the face of these challenges is a major strategic thrust of Balu's program, and the development of the advanced operator training simulator is a key element in that strategy.

Experience produces skill

The utility industry's interest in operator training simulators was spurred largely by the northeastern power blackouts of the 1960s and 1970s, which underscored the need to increase dispatchers' skills in dealing with emergencies.

The first generation of power system operator training simulators was demonstrated during the 1970s. These machines, known as stand-alone simulators, represented a generic power system and made it possible to display hypothetical situations to dispatchers, but they did not receive on-line data. Second-generation simulators received on-line data via a data link to the standby, or backup, computer of the utility's energy management system.

These early simulators, which are in use at some utilities, are helpful for teaching fundamental skills and normal, steady-state operation, but they fail to realistically model an entire power system. Also, they're slow. The simulator may not respond to a trainee's input for many seconds or even minutes, much longer than the 2 to 4 seconds in which an actual power system responds. Since time can be the dispatcher's main constraint during an emergency, such a lag in the simulated system's response could actually produce negative training—the trainee might learn to respond too slowly in situations that require rapid action.

In the early 1980s, EPRI set out to develop a third-generation simulator that would overcome the drawbacks of the earlier machines and provide the type of realistic training that would fully meet the industry's needs. The first step was to define guidelines that would provide a basis for the simulator's design. To do this, EPRI assembled a project team that included industrial psychologists; advisers from utilities with expertise in operator training, control center operation, and power system analysis; and experts from professional groups, such as the IEEE. The group issued a report in 1984, *Considerations in Designing and Using Power System Operator Training Simulators*, which established a vision of what EPRI's advanced simulator should be.

An exact replica

The simulator requirements spelled out by the project team, while being complex in terms of the computational effort involved, can be boiled down to one word: realism. The industrial psychologists emphasized that to ensure that trainees transferred the experience and skills acquired in the simulator to the real world, the training environment had to be authentic in every detail. The power system simulation must appear realistic to the trainees, and the representation of the control center should be exact, with the same displays, consoles, and controls used in the actual control room. The training environment should allow the trainees to see, hear, and feel what they would in the control center—to the extent that operating the simulator would be indistinguishable from operating the actual power system.

With the development of such a high-fidelity simulator as its overall goal, the project team produced a conceptual design to meet the requirements and then determined the software and hardware needed to satisfy this design. According to Curtice, in addition to being realistic, the simulator had to help support the instructors conducting the training sessions; and, perhaps most important, it had to be flexible enough for implementation by any utility. "Because we wanted to produce a training simulator that any utility could use, we had to develop a power system simulation that was completely portable."

Developing the software for the power system simulation was a major challenge. The OTS power system model represents the characteristics of equipment and components, including generating units, transmission circuits, and relays. The model simulates in real time the long-term dynamic behavior of the power system over a wide range of operating states—normal, emergency, and restorative. It can represent the system's response to a minor contingency or to a major perturbation like a thunderstorm, lightning, an earthquake, or a hurricane. "We broke new ground in modeling and algorithmic development to come up with a power system model with greater realism," says James G. Waight, manager of power systems analysis for Control Data's Empros Division. "It's now possible to simulate very complex phenomena, such as voltage collapse and certain aspects of system restoration, that previously could not be simulated."

"Perhaps the project's greatest achievement is that the power system simulation software was developed to run on any computer and in any control room," says Curtice. "The software can be transferred to any computer supporting standard Fortran and the language C." It is sufficiently robust to simulate the power systems of the largest utilities, he says. "All a utility has to do to model its system is enter its data in the database and fill in the system characteristics—generating units, line configurations, voltage levels, and so forth." The power system model will be available at no cost to EPRI member utilities.

Along with a realistic power simulation, the OTS required an exact representation of the control center. "In developing the OTS, we had to recognize that ev-

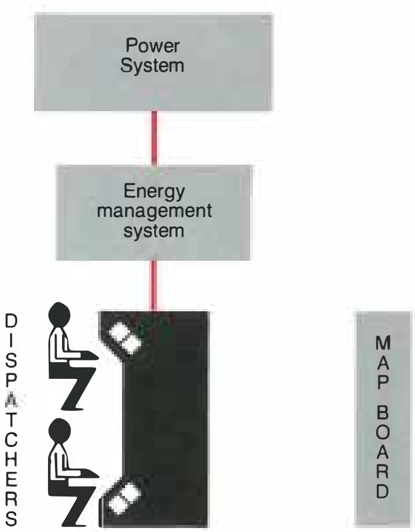
Simulating a Power System

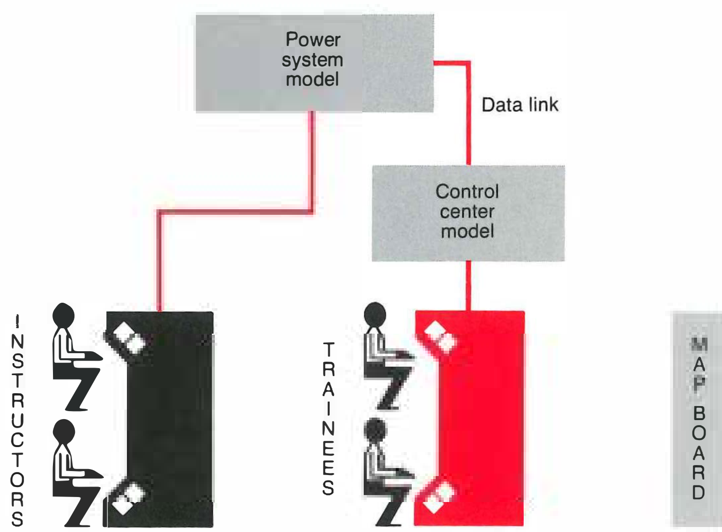
The Control Center

A big-picture view of the power system's status is displayed to control center operators on a map board and console-mounted monitors. Thousands of sensors installed in system components deliver a steady stream of real-time data, which are processed in the control center's computerized energy management system and graphically displayed to the operators.

The Operator Training Simulator

Operator trainees observe system conditions through monitors and a map board identical to those used in the control room. The characteristics of their utility's power system are captured in a power system model computer; a second computer contains the control center model, which runs the utility's own energy management system software. The two computers are connected by a data link, providing an exact replica of the trainees' work environment. This dual-computer configuration makes the operator training simulator an independent, portable unit adaptable to any utility's power system and energy control center.





ery utility has different equipment in its control center," Curtice says. While the power system model is composed of hardware and software that can be used by all utilities, the control center simulation had to be configured on the same type of hardware used in a particular utility's control center. For this reason, the OTS uses an innovative architecture that decouples the power system model and the control center model into distinct parts. The control center model is the utility's own energy management system software operating on a separate computer connected to the power system model through a communications interface. With this arrangement, the control center model receives information from the power system simulation instead of the actual utility power system.

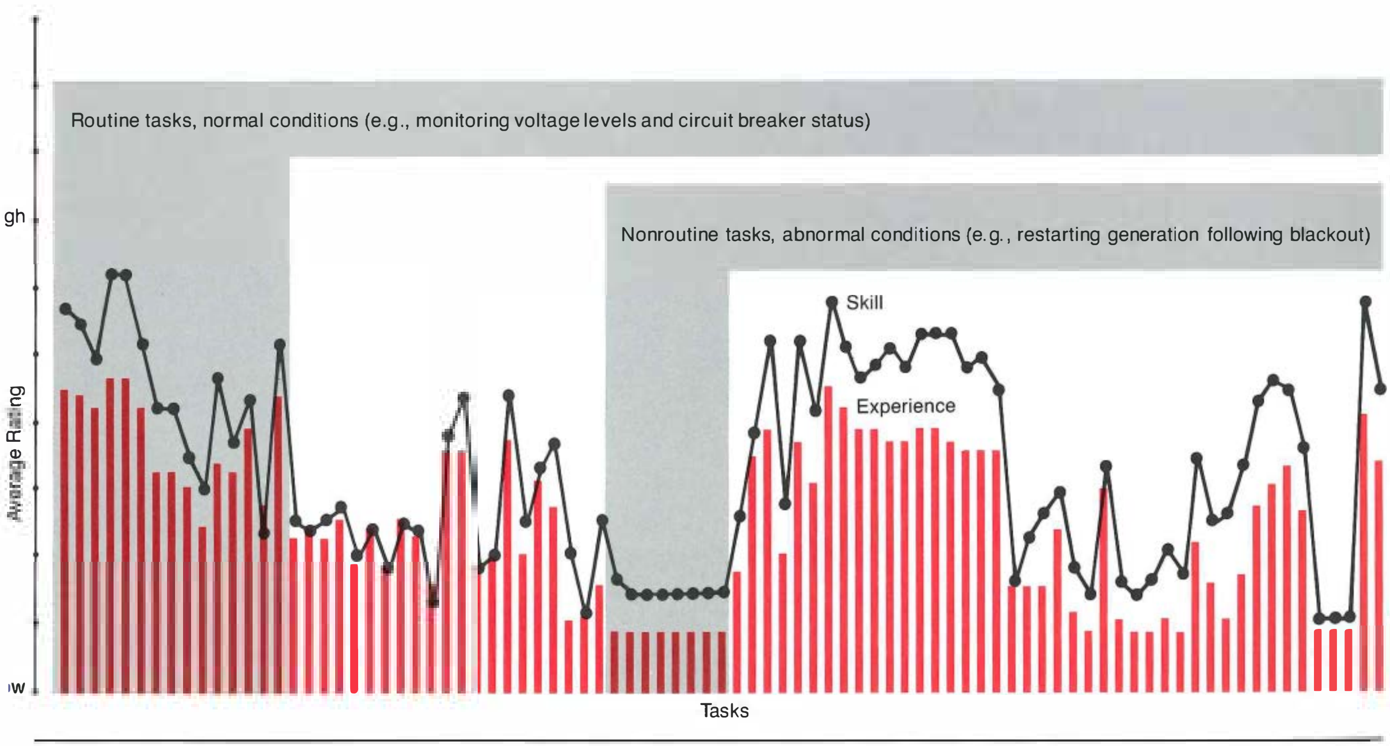
During a training session, the trainee sits at a console identical to the one in the control center. The trainee console is connected to the computer running the control center model. The trainee observes simulated system conditions on the console's displays and executes commands. The control center model computer processes these commands and sends signals over the communications interface to the power system model computer, which simulates the system's response. Throughout the session, the trainee's actions and the power system's responses can be viewed and evaluated by the instructor.

"Another aspect of the OTS that makes it a third-generation simulator is the support provided for instructors," says Curtice. "During training sessions the instructors may well have a heavier workload than the trainees. They have to monitor the trainees' actions, provide feedback, and introduce events into the simulation, such as a generator outage or the loss of a line. In addition, the instructors have to play the roles of plant operators and pool dispatchers over a telephone link to the trainees, so they're busy guys. That's why we developed a dedicated workstation for them."

This workstation contains features that allow an instructor to control and evaluate the training session. During the course of a session, he can stop and restart a training scenario, or pause it to explain a procedure to the trainee. There are also tools to help the instructor set up training scenarios, which can be a tedious and time-consuming task if performed

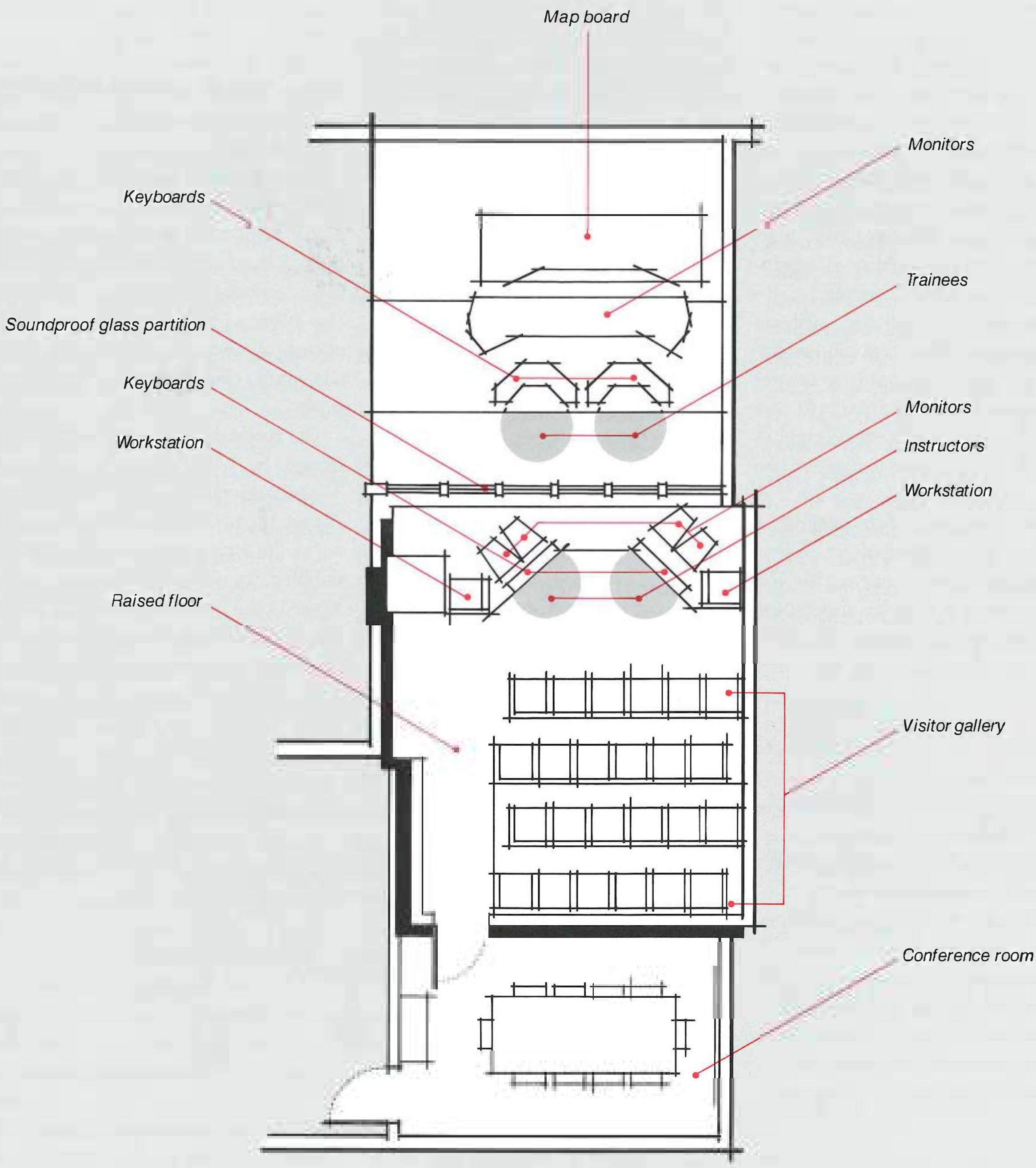
Assessing Experience and Skill

The skill of control center operators in performing certain tasks is, predictably, related to the amount of experience they have with those tasks. Operators' self-ratings of their skills in 87 routine and nonroutine tasks indicate that they have the least confidence about being able to respond to relatively rare, abnormal conditions. Simulator training is expected to raise operator skill levels, especially for nonroutine tasks, through repetition and iterative analysis.



True-to-Life Training at Philadelphia Electric

Realism is the dominant theme of Philadelphia Electric's simulator training facility. Operators will train in an environment that's a virtual clone of the utility's control room. Working on an elevated floor behind the trainees, instructors conduct the sessions, monitor the trainees' activities, and play the roles of plant operators, pool dispatchers, and substation operators over a telephone line to the trainees. The facility also has a conference room, where instructors and trainees meet to discuss the day's training session, and a gallery for visitors to observe the training program.



Map board
Monitors
Keyboards
Trainees
Soundproof glass partition
Keyboards
Monitors
Workstation
Instructors
Workstation
Raised floor
Visitor gallery
Conference room

A New Tutorial for Control Center Operators

Because safe and efficient power system performance rides on the expertise of energy control center operators, or dispatchers, EPRI's Electrical Systems Division has been working to improve the training of these key personnel. To complement the newly developed operator training simulator, the Power System Planning and Operations Program has published a tutorial that explains the dynamic behavior of interconnected power systems from the dispatcher's point of view. Intended primarily for training control center operators, the tutorial will also be useful to operators of steam and hydro power plants and to substation operators.

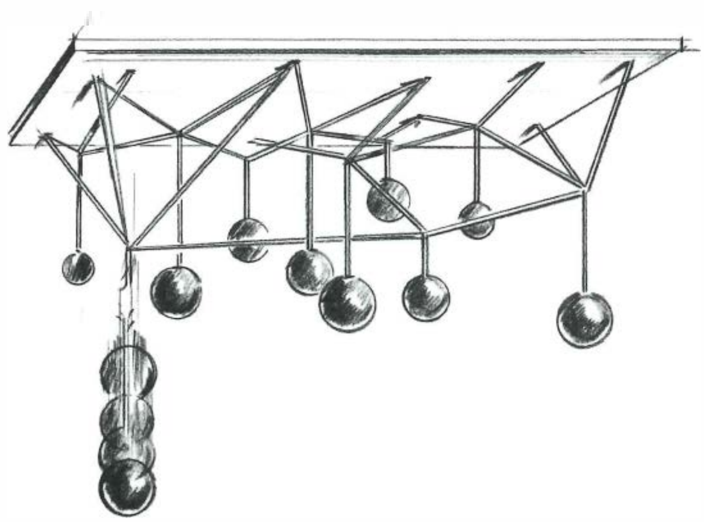
Entitled *Dynamics of Interconnected Power Systems: A Tutorial for System Dispatchers and Plant Operators*, the volume features an easy-to-understand format and avoids jargon. Electrical phenomena are described by using mechanical analogies instead of engineering terminology and equations, and system dynamics are illustrated with real-world examples. The material is organized with training objectives in mind, leading the reader logically through the development of concepts and reinforcing the concepts in summaries. The operator's role in solving system problems is emphasized throughout the text.

The tutorial begins with overviews of power system operation and dynamics, then explains specific dynamic phenomena, including frequency and voltage deviations, voltage collapse, and power system oscillations. Subsequent sections describe the effects of power plants and their control and protection devices on system dynamics, emphasizing coordination between the power plant and the power system.

The tutorial can also help prepare trainees for work in the operator training simulator, according to project manager David Curtice. "A trainee can read the tutorial's descriptions of a specific phenomenon—for example, voltage collapse—then go into the OTS and experience a voltage collapse in high fidelity."

The industry response to the tutorial has been enthusiastic, according to EPRI's Neal Balu. "We received more than a thousand orders in less than three months," he says. "There has also been a great expression of interest for follow-on materials, such as lesson plans, classroom aids, and videotapes."

The tutorial's value was recently affirmed by Larry Kinard, director of systems operations at TU Electric and chairman of the Operations Committee of the North American Electric Reliability Council (NERC). According to Kinard, the tutorial "scored a home run. It pulled into one text the material operators have needed for years." □



The tutorial uses mechanical analogies to explain complex electrical phenomena. In this analogy of power system oscillations, the weights represent the rotating mass of turbine generators and the rubber bands represent the inductance of transmission lines. Any disturbance, analogous to a pull on a weight, causes oscillations to be set up in all the synchronous machines in the system.

manually. A heuristic scenario builder, based on artificial intelligence and expert systems technology, speeds the process: it allows the instructor to specify the type of training scenario, level of difficulty, and trainee classification. Then it automatically constructs scenarios that meet the training specifications.

A world-class training facility

Philadelphia Electric, the host utility for the project, has implemented the OTS in a special set of dedicated rooms in what may be the world's most advanced operator training facility. In one room, two trainees sit at the same type of consoles used in the energy control center, facing a map board and strip charts identical to those in the center. Behind this mock-up is the instructor room, which has a raised floor to allow two instructors to observe the trainees through a glass partition. The facility also has a conference room, where instructors and trainees meet to review and plan the day's session, and a gallery, where visitors can view the training program.

The two-trainee, two-instructor arrangement provides several advantages. It allows two dispatchers to be trained simultaneously, in keeping with Philadelphia Electric's philosophy of using two dispatchers working as a team in the control center. Having two instructors adds realism to training and lightens the workload of each. While one instructor monitors the trainees' activities, the other conducts the training exercise and acts as the outside world, playing the roles of plant operator, pool dispatcher, and substation operator over a telephone line to the trainees. "We've given the instructors a sophisticated and automated support environment they didn't have before," notes Curtice.

EPRI is conducting seminars at Philadelphia Electric's training facility to demonstrate the OTS to member utilities interested in acquiring their own simulator. Control Data already has a license from EPRI to commercialize the OTS, and the Institute is working to get the technology commercialized through several other vendors of energy management systems.

Step-by-step development

Because the software used in the power system simulation model is portable, utilities can select from several options in putting together their own simulator-based training system. One approach involves starting out with just the power system model and then adding functions step by step, building up to a full training system. "Any member utility can get the power system simulation free of charge from the Electric Power Software Center and set it up on a workstation or any available computer," says Balu. "This minimizes the utility's up-front investment and allows its software engineers and support staff to become proficient in operating and modifying the power system simulation before embarking on a full-scale implementation." After getting acquainted with the power system model, the utility's next steps would be to add an instructor workstation and data-link the power system model to the energy management system.

Or a utility may decide to install an operator training simulator at the same time it acquires a new energy management system. In this case, the utility can review the OTS project documentation and use it in its request for proposal. Then the EMS vendors can propose to supply a training simulator with the same capabilities or obtain a license from EPRI and install the OTS software. Two utilities, Consolidated Edison and Bonneville Power Administration, have taken this approach in specifying new training simulators. Because the simulator is portable, the only custom work required involves establishing the interface between the EMS computer and the power system model.

Once the simulator is implemented, a utility may find that its usefulness extends beyond training control center operators. Since the OTS realistically represents the behavior of a utility's power system, it can be used by other personnel to better understand the system; moreover, it allows them to view it from the operator's perspective. This could prove especially useful in long-range planning for capacity additions, transmission configurations, interconnection capacity, and system restoration procedures. Once a plan is established, the simulator could be used to evaluate it in a realistic operating environment.

But the primary users of a training simulator are the men and women who bear the responsibility for keeping the nation's power systems running smoothly. As these systems grow more complex and are pushed to their limits, and as energy transfers involving utilities as well as nonutility generators become commonplace, improving the skills of control center operators becomes more critical. "Classroom and on-the-job training just can't fully prepare operators to respond to the full range of contingencies they may encounter," says Balu. "But this simulator can. By training in an environment that's so realistic it's indistinguishable from the real thing, dispatchers can acquire experience and skills that will allow them to deal confidently with a real system emergency." ■

Further reading

Proceedings: Power System Operations—Research Needs and Priorities. Report for RP2473-35, prepared by Barakat, Howard & Chamberlin, Inc. January 1990. EPRI EL-6659.

Dynamics of Interconnected Power Systems: A Tutorial for System Dispatchers and Plant Operators. Final report for RP2473-15, prepared by Power Technologies, Inc. May 1989. EPRI EL-6360L.

Implementing a Dispatcher Training Simulator. David Curtice and Robert Schulte. EPRI document, available on request.

Considerations in Designing and Using Power System Operator Training Simulators. Final report for RP1915-1, prepared by Electrocon International, Inc. April 1984. EPRI EL-3192.

This article was written by David Boutacoff. Background information was provided by Neal Balu and David Curtice, Electrical Systems Division.

TECH TRANSFER NEWS

New Hardfacing Alloy Wears Less Than Cobalt

A cobalt-free hardfacing alloy developed during five years of EPRI-sponsored research has been licensed to two international suppliers of welding materials. Trademark protection is being sought for the name NOREM, which reflects the absence of alloying elements that can become radioactive in reactor applications.

The alloy's first power industry use is expected to be in the valves of nuclear steam supply systems. It will also find use in other valves, pumps, and turbines throughout both nuclear and fossil fuel power plants.

The Stoody/Deloro Stellite divisions of St. Louis–based Thermadyne Industries are one licensee; Anval, a Swedish firm, is the other. Both companies are now producing NOREM alloys in powder form, with welding wire, welding rod, and castings to follow.

According to EPRI's Howard Ocken, who has managed the development effort, about 10 valve manufacturers have been evaluating NOREM during the past two years. "It's a real help for them to develop firsthand experience on their own terms," Ocken says, "but independent, objective full-scale tests are also being done by Atomic Energy of Canada, Ltd." The tests are long term and are using gate valves with NOREM hardfacing that was applied by the valve manufacturer—"just as fast and easily as cobalt alloys in the past," Ocken adds. The valves are operating under realistic PWR conditions of water pressure, temperature, and chemistry.

The test regimen (which will later be duplicated in a BWR system simulation) calls for 2000 open-close-open cycles, with nondestructive evaluation at 500-cycle intervals and destructive tests and analyses when the test is finished next fall. Ocken reports that valve examination after the first 1000 cycles showed NOREM to be performing better than cobalt hardfacing.

Until the advent of NOREM, cobalt was the major constituent (as much as 60%) of the best hardfacing alloys, those that wear least under the toughest conditions. Of special interest is resistance to galling, the wear that occurs when unlubricated surfaces rub together under very high stresses—they may even exchange material and thus bond or seize together.

Even the best hardfacing alloys are subject to wear and corrosion, and material that wears away from valves in the primary loop of nuclear steam systems may then be activated in the reactor core. In particular, the cobalt-59 isotope transmutes to radioactive cobalt-60, which "plates out" on other components or builds up in deposits, posing a problem of radiation exposure to maintenance crews. One major source of such cobalt wear is the globe valves used for PWR flow control just downstream from the demineralizers.

EPRI's research, conducted by AMAX Materials Research Center, sought an alloy that would avoid both the radiation potential and the fluctuating cost of cobalt. (Cobalt is a scarce and strategic material, mostly imported from a few African nations.) Nickel alloys pose a lesser radiation problem than cobalt alloys, but they also wear less well, meaning more frequent maintenance. The metallurgical research and testing by AMAX finally produced a carbide-strengthened austenitic stainless steel that resists wear and corrosion at least as well as cobalt alloys.

Up to now, the new NOREM alloy powder has been applied by the PTA (plasma transfer arc) process, in which the alloy powder is injected into an electric arc above the surface to be protected. PTA welding is an established shop procedure for equipment manufacturers and for major service facilities that replace hardfacing on component surfaces, but the advent of NOREM in rod and wire form will make for a wider range of field uses.

EPRI's Ocken notes that wear-resistant alloys are used "in everything from jet engines to artificial knee joints. By eliminating the need for cobalt, NOREM alloys can make a big dent in the billions of dollars spent every year to repair and replace worn parts." For information on NOREM availability, call Joe Hirscher of Thermadyne, (314) 746-2214, or Toby Tingskog of Anval, (800) 992-6825. ■ *EPRI Contact: Howard Ocken, (415) 855-2055*

More Power Won't Close This Generation Gap

A utility may have stable electricity rates and plenty of reliable capacity—and still suffer from what can genuinely be called a generation gap. For Wisconsin Public Service, the gap was a worrisome level of distrust of the utility by one of its largest group of customers, those aged 35 to 44—the so-called baby boomers.

A major step toward closing this "generation gap," WPS learned, was to take a leadership role in community issues and in promoting conservation. But most important was to involve itself more strongly—and eventually more credibly—with environmental matters.

WPS learned these and other sharp lessons from a mailed survey that drew a rewarding 70% response. Residential customers were asked to consider 51 electric utility service functions or attributes and rate each of them twice—first as to their importance and second as to WPS's level of performance. Ratings could range from 1 (lowest) to 7 (highest).

The six attributes of greatest importance proved to be (in descending order) accurate bills, honesty with the public, correct meter readings, quick response to outages, trustworthy employees, and knowledgeable employees.

Wisconsin Public Service by and large did well, points out Michael Kiefer, the utility's director of corporate communications. When the responses for each item were averaged, all 51 attributes were rated between 5.05 and 6.76 for importance, and WPS performance ratings were bunched within the same range—5.39 to 6.33. In fact, WPS drew three of its highest performance ratings for three of the most important items—accurate bills, correct readings, and knowledgeable employees.

Kiefer emphasizes that this basically high level of customer satisfaction didn't eliminate the utility's sense of uneasiness about certain customer groups. So statistical techniques were used to correlate and analyze the survey responses in order to illuminate problem areas.

The survey scores were analyzed in terms of several demographic groups defined by respondent age, education, income, and so on. This was when the well-educated, early middle aged customers—the baby boomers—were found to be less satisfied with WPS than other groups in the areas of management and leadership (cost management, initiatives in energy saving and efficiency) and trust and caring (environmental concern, honesty with the public, thought for the future).

The findings for these 35–44-year-old customers contrast markedly with the findings for the most senior age group, 65 and above, which registered the strongest positive scores for many of the same items.

Kiefer is quick to admit that "simply turning up the tempo" of conventional communication on the utility's conservation or environmental policies and activities won't work. "Our follow-up studies show that the baby boomers tune those messages out as unbelievable." Kiefer instead sees one-to-one initiatives with WPS customers as the way to establish believability.

What are some examples? "Home energy audits, community and environmental improvements—services that affect the customer's own health, safety, and welfare," says Kiefer. "We need to be involved with our customers directly, interpersonally. It's been awfully easy to think of electricity just as a commodity and not as a service for and with people."

For more information on the survey, write or call Wisconsin Public Service. ■ *Contact: Michael Kiefer, WPS director of corporate communications, P.O. Box 19002, Green Bay, Wisconsin 54307-9002; (414) 433-1620*

EPRI Research Damps Vibration of Lines

The problem of fatigue damage—including one instance of outright line failure—in conductors of Georgia Power's 500-kV transmission network has been solved with the aid of R&D results that helped the utility pinpoint the trouble spots. Selectivity in replacing corrective spacers along some 275 miles of line saved Georgia Power about $8 million.

The problem was wind-induced motion, called aeolian vibration, which can lead to mechanical fatigue of individual strands in bundled conductors; in extreme cases entire conductors, and the transmission line itself, may fail. Georgia Power found many places where one or two strands had broken right alongside the fastener clamps of the line spacers, which hold the conductors at the proper distance from each other.

Heading off potential line failure and the enormous costs of replacement power at first appeared to call not only for specific repairs but also for wholesale replacement of some 30,000 spacers. But Georgia Power instead took advantage of conductor fatigue research done for EPRI by Auburn University. Methods developed in field and laboratory studies there enabled the utility to correlate line vibrations with local wind conditions and predict which segments of line were most vulnerable to damage. Identifying those high-priority trouble spots meant that only about 6000 spacers had to be replaced; the savings were over $8 million.

The Auburn research on aeolian vibration also showed Georgia Power how to quantify the maximum permissible amplitude so as to avoid further damage. Using this information, the utility installed shock-absorbing devices called spacer-dampers at key points. The results of the Auburn University project have been published as *Conductor Fatigue Life Research* (EL-6607). ■ *EPRI Contact: Joe Porter, (202) 872-9222*

Operations and Maintenance

Nuclear Maintenance Applications Center

by Michael Downs, Nuclear Power Division

In 1984 the Nuclear Regulatory Commission increased its emphasis on maintenance improvements at U.S. nuclear power plants and in 1988 published a policy statement outlining its expectations in this area. The NRC will be closely monitoring industry progress in improving maintenance and will institute a maintenance rule if it believes adequate improvements are not made. To assist member utilities in improving the technical aspects of their maintenance efforts, EPRI created and provided for the startup of the Nuclear Maintenance Applications Center. A maintenance organization with international scope, NMAC is designed to provide practical and proven solutions to technical maintenance problems.

The NMAC concept had its origins in a $6.8 million EPRI project approved in December 1985. NMAC was started in 1987, and by late that year a steering committee was formed, with representatives from nine utilities and the Institute of Nuclear Power Operations (INPO). This steering committee, which now includes representation from 10 utilities, INPO, and the Nuclear Management and Resources Council (NUMARC), offers ongoing guidance and advice on NMAC operations, including the technical content of the center's work.

In 1988 NMAC was staffed by a director and two loan-in maintenance advisers; they were supported on a part-time basis by the Engineering and Operations Department staff of EPRI's Nuclear Power Division. NMAC currently has a director, three maintenance advisers, two utility loan-in advisers, and a secretary. By 1994 a staff of about 12 is anticipated.

ABSTRACT *To help member utilities continue to improve nuclear power plant maintenance, EPRI has created the Nuclear Maintenance Applications Center. NMAC develops and distributes the engineered results of utility maintenance experience in guides, memos, and hotline information. In addition to offering member utilities practical solutions to recurring, time-consuming, and expensive maintenance issues, NMAC provides a supportive technical advisory function.*

NMAC operations and products

The center concentrates on those technical areas for which no existing industry organization offers effective and practical help. Operating in a collaborative framework similar to that of EPRI as a whole, NMAC provides practical maintenance solutions—solutions that have been proved at one or more plants—to all member utilities, with a minimum investment of plant resources. NMAC does the legwork for a plant's maintenance and support personnel and minimizes the duplication of effort that occurs when several utilities independently attack the same maintenance problem.

NMAC pulls together existing information, then concentrates on the technical analysis and integration of that information. The results are conveyed to member utilities by means of technical documents, workshops, and other appropriate media. The accompanying list shows available technical documents and those under development.

One of the first technical documents to be published was NP-6229, a set of technical repair guidelines for Limitorque Model SMB-000 valve actuators. Despite the proliferation of motor-operated valve (MOV) applications at utilities and in other industries, practical, high-quality technical repair guides presenting accurate illustrations and step-by-step assembly and disassembly instructions were not available for the motor actuators. NMAC approached this problem by collecting the best knowledge available nationwide from utility maintenance organizations and from valve, actuator, and diagnostic equipment vendors. A group of 19 knowledgeable individuals, all with hands-on MOV maintenance experience, formed the technical advisory group for this project, which was chaired by NMAC's MOV specialists. NMAC used a contractor to write the first in a series of technical repair guides (TRGs). Illustrations, including exploded views of assemblies and parts, were developed by artists who observed expert technicians going through the process of assembling and disassembling a typical actuator.

The technical advisory group individually and collectively reviewed the TRG's initial and subsequent drafts. When the group reached an accord in late 1988, NP-6229 was published, presenting the best technical knowledge available in the most usable format. The TRG for Model SMB-00 actuators (NP-6631-D) and the *MOV Application Guide* (NP-6660-D) were developed similarly and were published in late 1989 and early 1990, respectively. The TRG for SMB-0 through -4 is being developed. All TRGs and application guides are presented in a loose-leaf format to allow for future revisions as technical improvements are made.

Two other early NMAC products, *Good Bolting Practices*, Vol. 1 (NP-5067) and *Storage and Handling of Diesel Oil for Standby Diesel Generator Systems* (NP-6314-D), took a different development path. Information for these guides was already available from many diverse sources. However, there were no practical, concise documents to serve as a ready reference for the maintenance worker with a basic knowledge of these subjects who occasionally needs some help on specific problems. To produce such documents, NMAC maintenance advisers worked with expert consultants, using their own knowledge and pulling information together from many diverse sources. The guides were reviewed during development by plant personnel.

A third tack was taken in the development of two other maintenance methods guides, *Freeze Sealing (Plugging) of Piping* (NP-6384-D) and *On-Line Leak Sealing* (NP-6523-D). NMAC maintenance advisers developed the conceptual basis and outline for each of these projects from discussions with utility plant personnel. Detailed technical input was obtained from service company experts, who then collaborated with the NMAC maintenance advisers in preparing the guides. Technical review was provided by utility and independent research laboratory personnel with extensive experience in the subject areas.

Several maintenance guides are being developed this year (see list). Utilities are providing significant input and review for these guides, and equipment suppliers are participating when appropriate. Workshops for EPRI members are scheduled this year in two important areas—infrared thermography and Terry turbine controls.

Maintenance hotline

Within EPRI there exists a wealth of expertise in maintenance-related technology. To help Institute members tap these resources, a toll-free number has been established—(800) 356-7448. Callers needing maintenance help are connected to an operator familiar with NMAC and with other EPRI maintenance-related applications (e.g., nondestructive evaluation, equipment monitoring and diagnostics, and service water maintenance). The call is then referred to an EPRI specialist who can discuss the utility's technical problem.

To enable NMAC to respond quickly to plant problems, the center's maintenance advisers are assembling a technical file of maintenance-related information screened from what is available through existing industry sources. NMAC acts as a central resource, consolidating and evaluating the data and, when necessary, following up with the sources. NMAC also opens access to international resources that may not normally be available to a utility.

The data file, along with the NMAC maintenance advisers' day-to-day contacts with plant maintenance personnel, will allow for the accumulation of a "memory" of NMAC member maintenance problems and solutions. Through this knowledge base, duplication of effort can be minimized, and improvements in techniques and methods can be made available to all members.

Benefits of NMAC membership

At present, all EPRI member utilities are automatically NMAC members. To demonstrate support for the center, some 30 U.S. utilities have voluntarily provided supplemental funding. Two foreign utilities have joined NMAC by paying dues. EPRI's primary financial role in NMAC has been to provide startup funding; by 1994 the bulk of NMAC financial support will come from membership dues. Utilities should be able to justify these expenditures through benefits provided by NMAC.

NMAC

Available Documents

- Technical repair guidelines for Limitorque SMB-000 (NP-6229)
- Technical repair guidelines for SMB-00 (NP-6631-D)
- Diesel fuel oil storage and handling guide (NP-6314-D)
- Freeze sealing guide (NP-6384-D)
- Good bolting practices, vol. 1: large bolts (NP-5067)
- Lube notes (memo)
- Guide for on-line leak sealing (NP-6523-D)
- Maintenance issues summary (memo)
- Circuit breaker guide (preliminary)
- Motor-operated valve application guide (NP-6660-D)

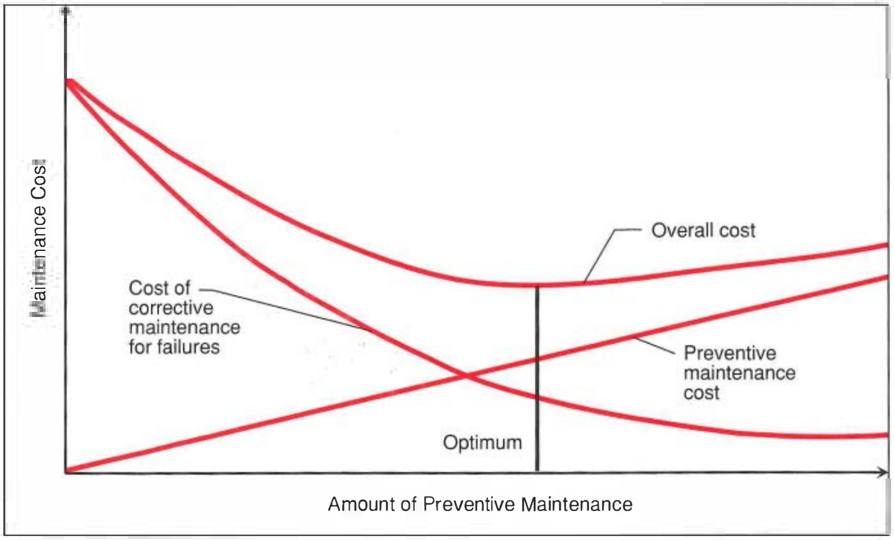
Documents Under Development

- Terry turbine controls guide
- Infrared thermography guide
- Primary and main steam safety valve guide
- Predictive maintenance guide
- Good bolting practices, vol. 2: small fasteners
- Technical repair guide for SMB-0 through -4
- Instrument air system guide
- Post maintenance testing guide
- Underwater maintenance guide
- Circuit breaker guide (vol. 1)
- Relays guide

By participating in NMAC, utilities benefit at the plant level, the utility level, and the industry level. At the plant level, specifically within the maintenance and maintenance support departments, NMAC—with its national and international perspective—can provide immediate, proven, cost-effective solutions to technical maintenance problems and can help utilities avoid duplication of effort.

NMAC can also assist in improving routine technical maintenance tasks by identifying cyclic failures. The costs associated with corrective maintenance for these failures are reduced through the implementation of technically effective preventive maintenance tasks (Figure 1). On the other hand, unnecessary or ineffective preventive tasks can be identified and eliminated or monitored, helping plants

Figure 1 Maintenance costs as a function of the amount of preventive maintenance. To achieve the optimum level of overall maintenance expenditures, utilities strive to identify and implement the best balance of corrective and preventive maintenance.



reduce any preventive maintenance backlog.

For the utility, the benefits of NMAC membership can accrue from improved plant reliability and safety system availability. Performance and heat rate improvements can result from technically effective maintenance actions. Much of what NMAC does is applicable to a utility's fossil or alternative fuel plants as well as to nuclear plants.

At the industry level, support of NMAC provides tangible evidence of a commitment to improve the technical aspects of nuclear power plant maintenance. The increased interest in regulatory activities relating to maintenance underscores the value of additional industry initiatives. The answer to improved maintenance does not lie with additional rules and regulations but rather with collaborative efforts, such as NMAC, that use the industry's vast resources to effect improvements.

Power Electronics and Controls

Power Electronics Technology Advances

by Ben Banerjee, Customer Systems Division

It is estimated that by the year 2000 approximately 60% of U.S. utility electrical output (kilowatthours) will pass through some form of power electronics conversion process. Power electronics and controls technology is interdisciplinary; each element of the technology has an impact on the others. Power electronics development efforts can provide utilities and their customers with a well-balanced, flexible set of technology alternatives to address energy efficiency, load growth/retention, load compatibility, product and power quality, productivity, and environmental impact. This update focuses on recent advances in circuits and controls and explores the value of integrated power electronics systems.

Circuits and controls

The objectives of work in this area are to accelerate the introduction of advanced power electronics circuit and control configurations into end-use applications and to develop comprehensive computer-aided design tools.

Some of the efforts under way address power quality (PQ) problems and solutions. The University of Minnesota is conducting a feasibility study of an input-harmonics-neutralized, single-phase uninterruptible power supply (UPS). Critical loads like computers normally have a dc power supply that produces a large amount of current harmonics. The project objective is to provide a standby power supply in which these harmonics are cost-effectively neutralized. The UPS assembly will incorporate a switch-mode inverter, a high-frequency transformer, and a cycloconverter. The next phase is to develop a three-phase prototype for field testing.

In a second PQ-related project, Westinghouse is developing an active power-line-conditioning system for compensation of input voltage harmonics and output current harmonics and for voltage regulation. Future development work may add such features as unbalanced-voltage compensation, momentary-voltage-loss ride-through, surge suppression, and power factor correction. A 115/230-V single-phase 60-Hz, 5-kVA prototype has already been developed and will be field-tested with Public Service Electric & Gas. Next a three-phase 150-kVA prototype will be developed for field testing. Westinghouse, in cooperation with EPRI, will conduct market and manufacturability analyses to determine commercial, utility, and military requirements in the active power-conditioning area.

Several other projects on circuits and controls are also proceeding. One focuses on the specification and selection of power-switching devices and components for adjustable-speed drive (ASD) applications. The contractor, McCleer Power, is summarizing the detailed design considerations involved in specifying and selecting such devices as thyristors and such energy storage components as capacitors and inductors. The project will provide utility engineers and end-use customers with a time-saving guidebook on cost-effective ASD design and application.

Efforts by the Power Electronics Applications Center (PEAC) and the University of Tennessee at Knoxville (UTK) include a demonstration of insulated-gate bipolar transistors and metal oxide semiconductor–controlled thyristors in ac motor drives using advanced resonant-link circuits. The system provides several performance advantages—higher switching frequency, reduced harmonic distortion and control complexity, and improved circuit efficiency and reliability—at reduced weight, size, and cost. A 5-hp prototype is currently under development. PEAC and UTK are also developing sensorless control of permanent-magnet motors; this will eliminate the need for a rotor-position sensor, reduce cost and control complexity, and increase control system and product reliability.

Finally, under an exploratory research contract (RP8000-40), PEAC and UTK are investigating the use of expert systems in ASD design and control. One objective is to develop an automated system for the selection and specification of circuits, devices, and components and the design of control systems. Such an automated system would not require specific system and motor parameters at the design stage. It would lower ASD manufacturing time and cost and improve reliability.

Other research

Along with the advances in circuits and controls, EPRI is making progress in the areas of devices and components (RP3088) and advanced motor systems (RP3087). Research on devices and components covers applications enhancement for power-switching devices and passive components (e.g., capacitors, inductors) and the use of new materials to bring such promising technologies as smart solid-state circuit breakers from the laboratory to commercial reality. Advances in passive components can reduce their size and cost by almost half.

Perhaps one of the greatest opportunities to improve national energy efficiency and protect the environment lies in the development of the next generation of motor/drive systems. Advanced technologies like permanent-magnet synchronous motors can reach energy efficiency levels of over 95%, operate at variable

ABSTRACT *Power electronics deals with the conversion and control of electric power in various industrial, commercial, residential, municipal, transportation, and utility applications. Utilities are just beginning to understand how to apply power electronics to improve the efficiency and operational flexibility of end-use products. The objective of EPRI's research in this area is to generate new or improved power electronics technologies like adjustable-speed drives, uninterruptible power supplies, active power-line conditioners, and smart solid-state circuit breakers.*

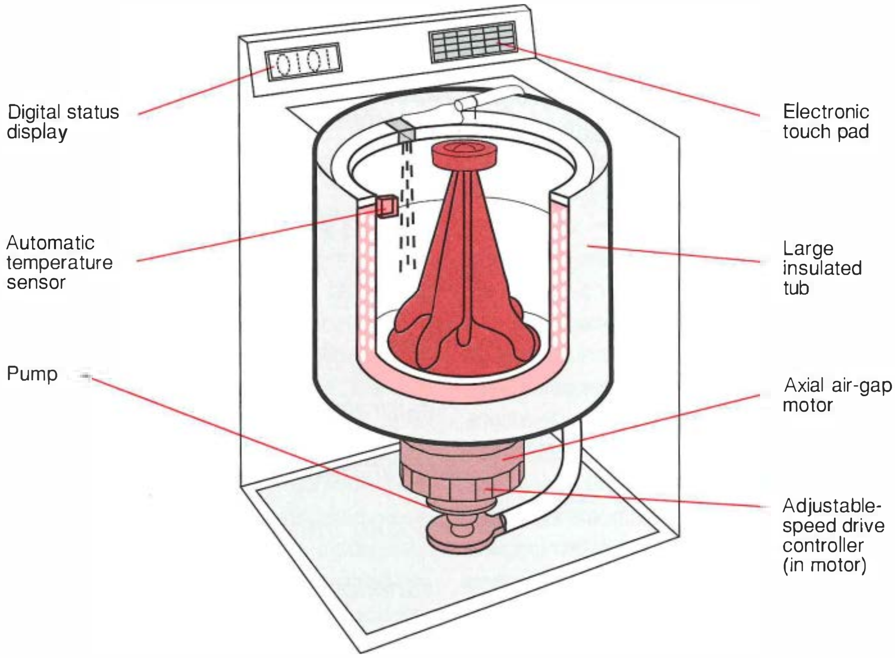


Figure 1 The development of this advanced automatic washer is an example of how power electronics advances in the areas of circuits and controls, devices and components, and motor systems can be integrated into specific end-use applications. Such integration is key to the commercialization of these advances.

speeds, achieve high speeds (>15,000 rpm), and allow size and cost reductions in the systems that house them (e.g., compressors). Over 60% of all U.S. electricity flows through a motor on the way to its application. If a 10% improvement in motor system efficiency can be cost-effectively made, the impact on the nation's energy future will be significant.

Technology integration

For specific end-use applications, it is necessary to integrate several areas of power electronics advances (e.g., circuits and controls, devices and components, and motor systems). Otherwise, the advances in individual areas may become isolated on-the-shelf possibilities rather than commercialized realities.

An example of such integration for a specific end-use application is the advanced automatic washer shown in Figure 1. It features a direct-coupled advanced motor—the ASD is housed inside the motor by means of advanced packaging technology. This motor and drive combination would eliminate most or all of the transmission and drivebelt requirements in the washer; it can also be designed to operate in a clean power mode (no input current harmonics). The advanced motor design can provide higher energy efficiency and better performance.

There are many other opportunities for the near-term integration of advanced power electronics technologies into commercial products—for example, power tools; heating, ventilating, and air conditioning systems; heat pumps; and the electric vehicle ac drivetrain.

Land and Water Quality

UDEX: Unsaturated-Zone Dispersion Experiment

by Dave McIntosh, Environment Division

ABSTRACT *Monitoring the chemicals released from utility waste disposal sites remains a pressing industry challenge. One part of EPRI's ongoing solid-waste environmental studies project, the unsaturated-zone dispersion experiment, sought to determine how contaminants spread and are diluted in the unsaturated subsurface. Solute transport was found to be influenced significantly by vertical variations in soil properties. The field data on dispersion acquired in this study will provide the basis for simulations of contaminant transport and fate.*

The EPRI solid-waste environmental studies (SWES) project (RP2485) is a comprehensive research effort aimed at developing methods to predict the transport, transformation, and fate of chemicals released from utility waste disposal sites. An important component of this project is the study of dispersive transport of contaminant plumes in the subsurface. Dispersive transport is the process that gives rise to the spreading and dilution of contaminants in the subsurface. The unsaturated-zone dispersion experiment (UDEX) consisted of two field-scale tracer experiments to measure the hydraulic and dispersive characteristics of the unsaturated zone (RP2485-6). Related studies of the saturated groundwater zone (the macrodispersion experiment) are being conducted under RP-2485-5.

This research is motivated by the significant role of dispersive transport in determining the disposition of contaminant plumes emanating from waste disposal sites. Information on the macrodispersive characteristics of the unsaturated zone is required input to hydrogeochemical codes that predict the transport, transformation, and fate of chemicals in the subsurface. The accurate characterization of dispersion is therefore crucial to the application of models to predict the environmental impacts of waste disposal facilities.

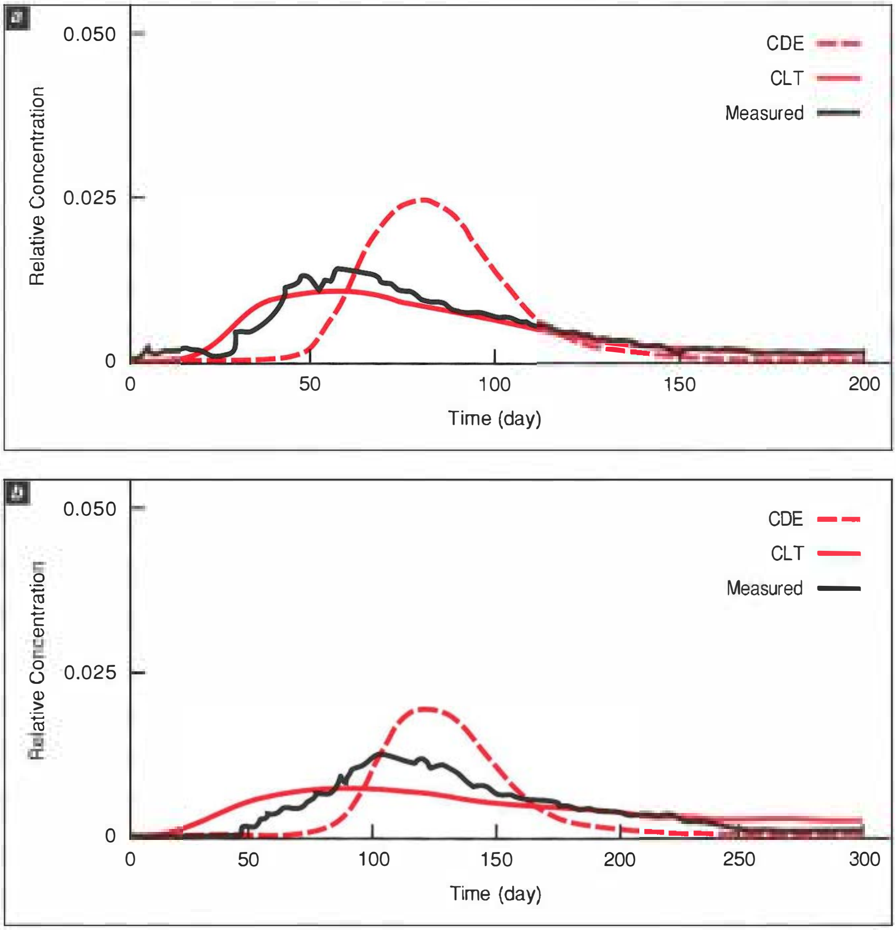
Large-scale study

Two large-scale field experiments, cosponsored by Southern California Edison (SCE), introduced tracers into the subsurface to investigate the nature of dispersion in the unsaturated zone and to quantify dispersivity as a function of the hydraulic properties of the sites. The majority of past experimental studies of chemical transport through the unsaturated zone overlying groundwater have been conducted in laboratory soil columns or shallow, small-area field plots. Consequently, there is a dearth of information and understanding concerning the field-scale solute transport processes that govern the downward movement and mixing of dissolved chemicals over large land areas and to significant depths. Two field sites with very different soil textures were selected for the experiments. One study took place in a sandy loam soil in the Moreno Valley, 20 miles from Riverside, California. The other study, the focus of this report, was performed at an SCE-owned field site in Etiwanda, California, approximately 15 miles west of Riverside.

The unsaturated zone at the Etiwanda site extends to over 150 m, providing ample opportunity for the development of a tracer plume. The soil at the site is nearly level Tujunga loamy sand. The dominant textural features are a gravel layer near the 1.2-m depth and a finer-grained soil in the neighborhood of 3 m. Soil cores taken to 25 m revealed variable alluvial layers of sands, coarse sands with gravel, and loams.

In the large-scale experiment at the Etiwanda site, an irrigation system was used to apply a narrow pulse of an inert, nonadsorbing tracer—sodium bromide (NaBr)—onto a 6400-m^2 field. The application of tracer lasted for 30 minutes and was followed by irrigation with fresh water for 2.5 hours. This initial introduction of the tracer was followed by applications of 1.5–2.5 cm of water every other day for eight months. Samples were extracted at 16 locations to track the migration of the NaBr plume. The sampling locations were arranged in a four-by-four grid, 20 m apart, and outfitted with ceramic suction lysimeters at depths of 30, 60, 90, 120, 180, and 305 cm. Six of these locations were equipped with an additional sampler at 450 cm. After the eight-month experiment ended and irrigation was terminated, 32.5 cm of rainfall over the next 12 months contributed to further downward displacement of the plume. After the additional rainfall, the plume was sampled by taking six soil cores to a depth of 25 m, and the vertical profile of bromide concentrations was established.

Figure 1 Predictions from two transport models, the CDE and the CLT, are compared with actual measurements of the temporal change of solute concentration at depths of (a) 3 m and (b) 4.5 m. The model predictions are based on calibration parameters derived from measurements at 0.3 m. The CLT gives a more accurate estimate of concentration at 3 m; both models are inaccurate for the 4.5-m depth, which demonstrates the need for further theoretical development.

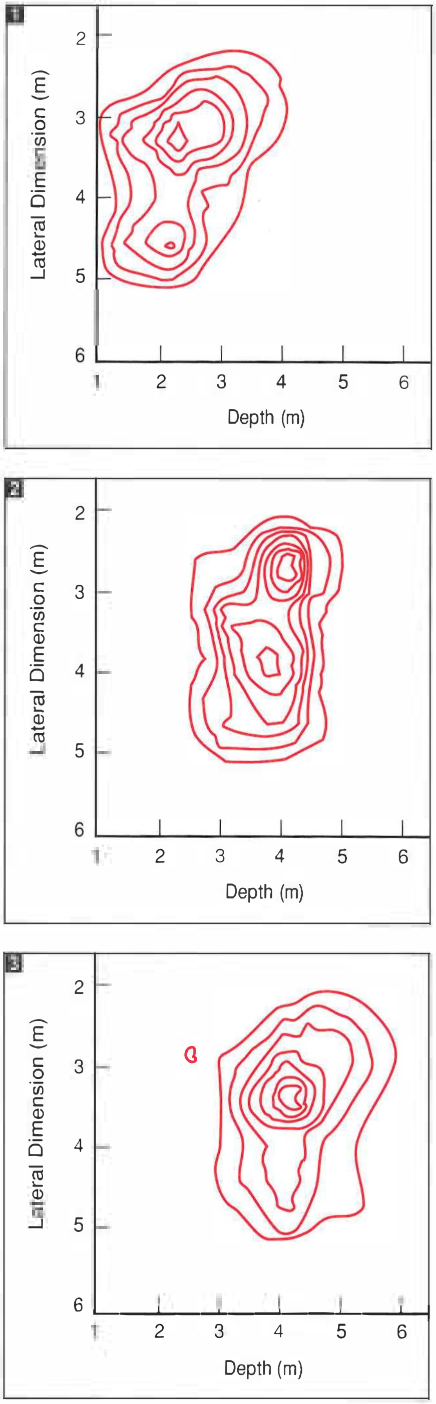


The data on the three-dimensional distribution of bromide concentrations were used to determine dispersivity. In addition, the data were used to test the validity of two transport models—the convective lognormal transfer function model (CLT) and the convective-dispersive equation (CDE). The validation procedure required calibration of the models with data from the first 0.3 m of plume migration. These model parameters were subsequently used to predict plume behavior at locations beyond 0.3 m. The predictions were then compared with field measurements.

The objective of the experiment was to study the longitudinal spreading, or dispersion, of the area-averaged pulse as it moved downward. The results show that the dispersivity increased linearly between depths of 0.3 and 3 m, leading researchers to conclude that in this zone lateral differences in the downward water velocity were not being smoothed out by transverse mixing.

At the 4.5-m depth, the dispersivity decreased to 70% of its value at 3 m. This behavior is theoretically impossible in a macroscopically homogeneous soil profile. Therefore, it was speculated that the dispersivity decrease might be attributable to increased lateral spreading caused by an increase in clay content in this zone. The decrease sug-

Figure 2 Examples of two-dimensional perspective of a chloride plume in the areally uniform moisture experiment. The second sampling clearly shows compression of the plume at a depth of about 4.5 m, suggesting a mechanism for the decrease in dispersivity observed in the large-scale experiment.



gests that detailed subsurface characterization is required for describing dispersive behavior.

The final soil coring produced a bimodal average concentration profile with a main peak located between 10 and 15 m and a secondary maximum between 20 and 25 m. When the entire profile was considered, the apparent dispersivity was almost four times as large as it was at 4.5 m.

The one-dimensional CDE, commonly used to describe chemical movement under areally uniform water applications, seriously underpredicted solute spreading when its parameters were calibrated in the near-surface regime. The CDE predicted peak concentrations 71% greater than the measured values. In contrast, the CLT described the pulse spreading through the top 3 m very well (within 22% of measured peak concentrations) after calibration at the shallow depth. The CDE and CLT predictions for the 3-m depth are presented in Figure 1a, along with measured concentration distributions. Beyond the 3-m depth and the textural boundary, the CLT also failed to predict measured concentrations accurately (Figure 1b).

The large-scale experiment demonstrated conclusively that the dispersivity values were changing even after 25 m of travel. Consequently, the failure of the CDE—a constant-dispersivity model—was not surprising. On the other hand, the CLT worked well to a transport distance of 3 m but failed beyond that point because the textural change required recalibration. The other significant finding was the decrease in dispersivity that occurred in the vicinity of the clay layer. It was apparent that the decrease resulted from the textural change in the 2–4.5-m region. One possible phenomenon that may cause the decrease is an increase in lateral mixing (i.e., transverse dispersivity) at the boundary between the fine and coarse soils. This hypothesis was tested in three-dimensional plot experiments.

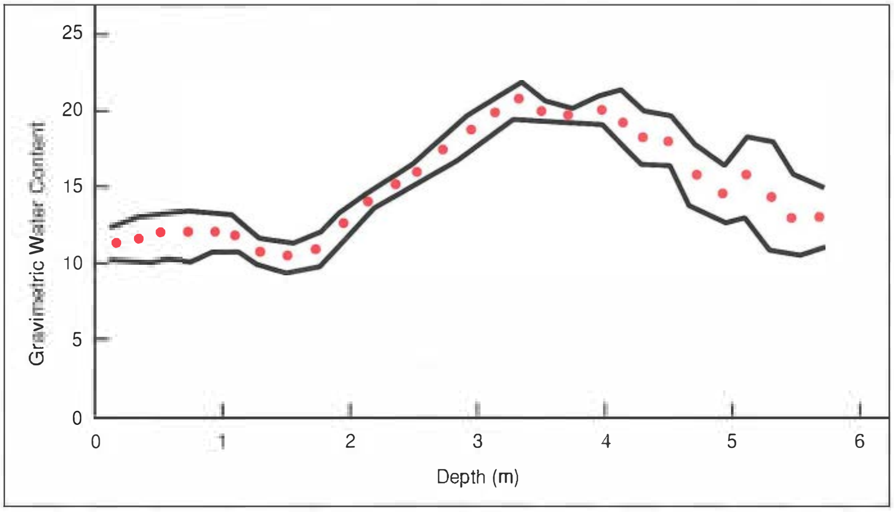
Three-dimensional plot study

The initial increase and subsequent decrease in dispersivity measured during the large-scale experiment were clearly caused by the soil heterogeneity in the direction of flow. The role of local transverse spreading in producing the results could not be deduced from the one-dimensional study. As a result, a three-dimensional field experiment was designed for measuring transverse as well as longitudinal dispersion. The objectives were to obtain quantitative concentration distributions of a tracer plume moving through the unsaturated zone, to characterize the degree of transverse and longitudinal spreading during the plume's passage through layers of different texture, and to develop a database from which model assumptions could be validated and new theories developed. With these aims, the researchers ran 13 plot experiments at the Etiwanda site using various tracers, tracer application methods, initial moisture conditions, plot dimensions, and sampling strategies.

Three inorganic tracers (chloride, nitrate, and borate) and one organic tracer (m-TFMB) were used. Nine of the plots each received (through a drip emitter system) a daily tracer application over a two-week period while the area surrounding each plot was irrigated with fresh water at an equivalent rate. After a tracer application period that permitted the development of a cubic tracer plume, the entire field was irrigated daily with fresh water. The 1.5-by-1.5-m plots were destructively sampled by soil coring, while the 2-by-2-m plots were sampled on three occasions. As a result of the tracer application method, the entire field developed similar moisture content profiles. To examine the effects of soil moisture conditions, one experiment was conducted with the tracer plume developing in initially dry surroundings. To add further insight into the dispersive transport process, another series of experiments was performed in which the tracer plume was allowed to develop from a resident volume (2 by 2 by 0.05 m) of tracer-spiked soil rather than by the drip emitter system; in this case, the solute tracer was transported into the subsurface by daily irrigations with fresh water.

The results of the steady-state water flux and uniform moisture content profile experiments suggest that transverse solute spreading was less than 50 cm after 5 m of vertical

Figure 3 Field-averaged gravimetric water content. An increase in moisture content in the vicinity of the textural change at 4.5 m is evidence of solute accumulation associated with plume compression.



plume migration. It was also apparent from these results that soil textural variations did not induce significant increases in transverse spreading. This observation is particularly relevant to the interpretation of results from the large-scale experiment. The speculation that a decrease in longitudinal dispersivity resulted from increased lateral spreading at the textural interface now appears to be altogether wrong. The results of the three-dimensional plot experiments lead to the conclusion that the compression of the plume at the textural boundary (and the associated decrease in dispersivity) is effected by a change in storage, that is, an increased moisture content in this zone (Figures 2 and 3).

Transverse spreading increased significantly during the experiment in which the soil surrounding the plume was relatively dry. Spreading of 200 cm, compared with 50 cm for the uniform moisture content case, reveals the importance of lateral transport driven by lateral gradients in matric potential. The experiment in which the tracer was resident in the soil before irrigation resulted in plumes that encompassed a smaller volume of soil than the plumes in the flux experiments. The results also show significant vertical dispersion, considering that the tracer was initially present in a 5-cm band and that at the time of sampling it encompassed a volume 25 times greater than its initial volume.

Interpreting the findings

These experiments have provided a great deal of insight into the solute transport process that occurs in the unsaturated zone: vertical variability in soil properties was found to have a significant influence on vertical plume spreading; transverse plume spreading was found to be dramatically enhanced in an initially dry environment. However, the failure of the CDE model at all depths and the invalidity of the CLT model beyond the 3-m depth leave us without a theoretical framework for interpreting this information. From a practical point of view, there remains the need to develop methodologies to predict dispersive behavior on the basis of physical site characterization.

The results of this work are applicable to a variety of utility concerns related to contaminant spills or leaking disposal sites. The available field data on dispersivity in the unsaturated zone provide reasonable estimates of this parameter for hydrogeochemical simulations of contaminant transport and fate.

Transmission Substations

Digital Control and Protection Systems

by Larry Mankoff, Electrical Systems Division

Electromechanical or solid-state analog single-function devices have traditionally met the requirements of protective relaying, control, monitoring, and communication for transmission, distribution, and generating stations. However, major advances in digital technology—including high-speed microprocessors, digital memory capability, fiber-optic communication, and advanced displays—now enable utilities to reduce costs and enhance performance in this area.

Building on early research that used commercial minicomputers, EPRI recognized this opportunity and began to apply digital technology advances to transmission and distribution automation in the late 1970s. These research projects have resulted in two key benefits to the utility industry: EPRI efforts have spurred industry application of digital technology to single-function devices for protective relaying and fault recording, and EPRI has helped develop and demonstrate integrated digital systems for transmission substations. Both of these developments have helped, and

ABSTRACT *In typical transmission substations today, sets of single-function devices are used for protection, control, monitoring, and communication. In the late 1970s, EPRI began to develop digital microprocessor technology for application in these areas. This advanced-technology effort has benefited utilities in two ways. First, it has helped provide single-function devices for protective relaying and fault recording. Second, and of equal importance, EPRI has developed an integrated system for substations and associated transmission lines. The system, which has been successfully demonstrated at several utilities, can be used in new or expanded substations or in retrofit applications.*

will continue to help, utilities realize the benefits of digital technology in substation protection, control, monitoring, and communication.

Utilities must examine several factors to determine whether to install single-function devices or an integrated system. The analysis should include comparisons of functionality, first costs, installation costs, startup costs, expected maintenance costs, and interest costs. For a given level of functionality, an integrated system can be a lower-cost alternative than a system made up of single-function devices. Moreover, the use of digital microprocessor technology has made practical a number of added protective relaying and other functions. While some of these functions can be applied when using single-function devices, many require the capabilities of an integrated system, and almost all can be accomplished at lower cost with an integrated system.

Integrated systems can be installed in new substations or in the major refurbishment of existing substations. Even in cases where only one relay is being replaced, total system replacement of obsolete equipment should be considered; retrofitting a single-function device into an old substation may be difficult and expensive, and the new system—with its added functionality, lower maintenance costs, and improved reliability—may pay for itself.

Integrated system

With the new integrated, microprocessor-based system for substations and associated transmission lines, short cable runs can bring signals to data acquisition units, where the data are converted to digital form and transmitted via fiber-optic communication channels to the control house. This arrangement, as well as the multiple use of substation information, reduces cabling needs. In addition, electromagnetic interference is reduced, and system performance is improved. For some retrofit applications, conventional cabling can be accommodated.

In field installations to date, this new system has been reliable, efficient, and cost-effective. EPRI-sponsored demonstration projects at Public Service Electric & Gas (PSE&G) and the Tennessee Valley Authority (TVA) have proved the system's applicability to new or expanded substations as well as its retrofit potential. Replacing obsolete control subsystems piece by piece often entails extensive on-site fitting, rewiring, and checking. In the long run, installing a new factory-built and -tested system can lower costs and enhance performance.

The new substation protection, control, and monitoring system was designed to meet the following performance criteria:

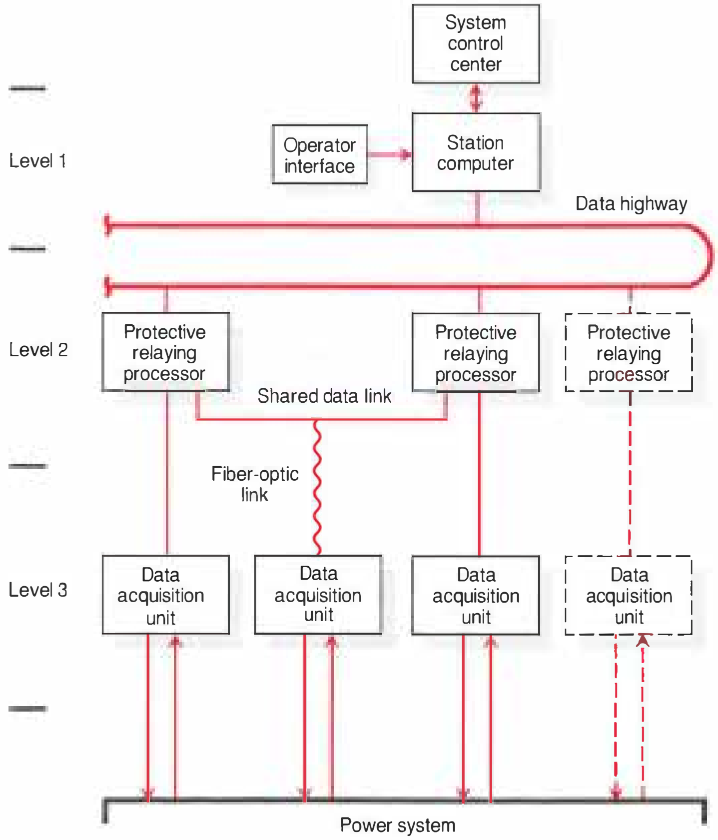
- The critical protective relays must operate even if the substation computer fails.
- If any single component fails, the system must still be able to perform all critical processing.
- To ensure economic viability, the system must not require more than one completely redundant data-gathering process to satisfy the above criteria.

To meet these requirements, which are detailed in EL-6592, EPRI developed a three-level system architecture (Figure 1). Level 1 involves functions common to the whole substation; it includes a data highway and an operator interface that allow operators to communicate with the entire system. Level 2 encompasses all critical processing, including protective relaying functions. Level 3 is the interface with the power system, where data are digitized for transmission to the protective relaying processors. At this level, control commands from the system control center and from levels 1 and 2 are converted to outputs that operate the power equipment (e.g., breakers and switches).

The communication equipment between levels is a key element in the system. Each processor must be able to communicate with every other processor, large amounts of data must be communicated quickly, and the system must be open and easily expandable. To meet these needs, a communication interface specification was developed and tested as part of the project. For communications between levels 1 and 2, a common, easily expandable high-speed data highway is used. Economical large-scale integrated circuit technologies enable a speed of 1 megabit per second. In the case of data highway failure, the system is designed so that critical protective functions will still be performed.

In cases where data acquisition units (DAUs) are placed in the substation switchyard, data links between levels 2 and 3 use

Figure 1 A three-level system architecture is used in the integrated protection, control, monitoring, and communication system for substations. Level 1 enables operator communication with the system; level 2 processes the data received from the data acquisition units in level 3.



optical fibers. If conventional control wiring between the yard and the relay house is available, however, these fibers may not be needed and the DAUs can be located in the relay house.

PSE&G demonstration

The integrated protection and control system was first installed at the 500-kV Deans transmission substation of PSE&G. The Deans system has a station computer, four protection clusters, and seven DAUs (Figure 2). The system provides bus, transformer, and line protection and is arranged so that each DAU is connected to one or more protection clusters. Two of the DAUs are located in the switchyard and transmit signals via fiber-optic cables; the others are located inside the control house, along with the rest of the system equipment.

The detailed communication interface specification developed by EPRI ensures compatibility between DAUs developed by different manufacturers.

The data highway connects the station computer to the protection clusters, and data links connect the protection clusters to the DAUs and the external interfaces. The station computer communicates with a supervisory control and data acquisition (SCADA) master, a protection engineer's console at the utility offices, and remote and local printers for logging sequence-of-event messages.

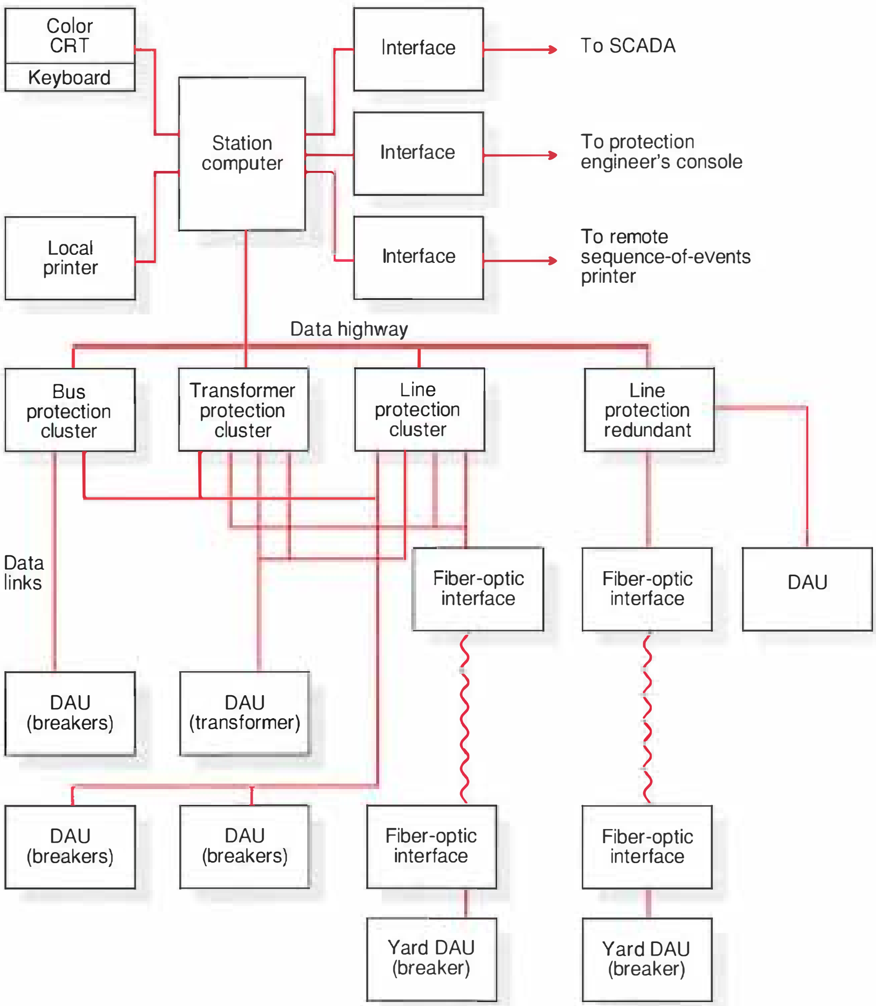
A clock connected to each protection cluster and the station computer synchronizes system operation with power system frequency. The system also has a central fixed-frequency (960-Hz) clock for use in case of line-frequency-tracker failure. The timing pulses are then communicated to each DAU through the data links.

Each signal in the station is sampled at the same instant (i.e., within about 25 microseconds). During each sampling interval of 1.04 milliseconds (corresponding to 16 samples per cycle at 60 Hz), a full complement of instantaneous ac quantities and contact inputs is converted, formatted, and sent over the data link from each DAU. Also, control messages are relayed to the DAUs during each interval. After each protection cluster receives the raw data, high-speed relaying and control programs evaluate sequences of instantaneous samples for signs of power system faults and extract accurate phasor measurements of ac signals.

The station computer stores the data from the protection clusters in a central database for local display and transmission to other sites. The database contains periodic phasor values of ac signals (1- or 0.1-second period), the status of power apparatus, the internal status of programs and hardware modules, sequence-of-event messages generated at the protection cluster or the station computer level, and fault data samples to support oscillography and other fault evaluation functions. The station computer also executes manual or automatic control operations (e.g., slow-speed reclosure) that do not require the speed of fault protection. Finally, the station computer provides operator interface and communication functions.

While the Deans substation system provides only for communication from the substation to remote locations, subsequent designs permit communication both to and from remote locations. Thus, in addition to receiving information from the substation on status, settings, limits, and the like, an off-site operator or protection engineer can enter setting changes and download them to the substation equipment. This ability to modify substation operation from a remote location in response to changing power system conditions is particularly convenient in the case of hard-to-reach (e.g., hilltop) substations. As a safeguard, the system uses a security program with a callback feature that requires proper

Figure 2 **The system demonstrated at PSE&G's 500-kV Deans transmission substation consists of a station computer, input and output devices, protection clusters, and data acquisition units (DAUs). Featuring bus, transformer, and line protection, the system uses both switchyard and control house DAUs.**



identification to change settings and prevents unauthorized access.

Stand-alone terminals

In addition to the integrated system for transmission substations, EPRI has developed a protection, control, and monitoring system for transmission lines. This system uses either conventional, wired connections to yard equipment or a remote (yard-located) DAU with a fiber-optic link.

The system was first installed at the Branchburg end of PSE&G's 500-kV Deans-Branchburg line. Each of the two protection terminals in this installation has four functional units—the protection module, the data acquisition and control system, the local man-machine interface (MMI) subsystem, and a conventional carrier set. In accordance with assigned security codes, the MMI function allows the operator to initialize and operate the system and to change protection and control settings. The MMI also logs faults and events, fault type, fault location, current magnitude, protective relay time, sequences of events, and more. On command, the MMI provides complete digital system settings for operator or relay engineer review, and it can communicate with a protection engineer at a remote console.

In addition to these line protection terminals at Branchburg, 12 more have been built and installed at Carolina Power & Light, Georgia Power, Northern States Power, Philadelphia Electric, Southern California Edison, and TVA as part of EPRI's demonstration program. Also, the Empire State Electric Energy Research Corp. (ESEERCO) has funded demonstrations featuring the EPRI design at Consolidated Edison of New York, Rochester Gas & Electric, and Niagara Mohawk. The terminals being used are similar to the line protection elements of the Deans system, and each can later be integrated into a complete substation computer system, if desired. The large number of demonstration sites provides for exposure of the technology to a variety of electrical and environmental conditions.

Benefits

In addition to having a lower first cost and lower operating and maintenance costs, the new integrated system is more flexible than traditional substation control and protection systems. Changing control requirements, station expansion, and station modification require periodic modification of substation control systems. Because the new system is software based, utilities can add functions or modify existing functions with minimal hardware changes.

With conventional systems, individual control panels and considerable control cable and wiring are installed at the substation—a labor-intensive process. This extensive interconnection necessitates comprehensive testing. In the new system, cabling is reduced because of the multiple use of substation information and the integration of many functions into common hardware. Where applied, fiber-optic cable operating in a multiplex mode between switchyard equipment and the control house significantly reduces cable requirements. Also, factory testing reduces onsite labor costs and installation time. And the integrated control system requires less space, reducing control house size.

To ensure proper operation, self-checking software provided with the automated system continually monitors all functions. This software alerts operators of a hardware or software failure and identifies the failure location, minimizing repair time and costs.

The new system can perform functions at a lower cost, including sequence-of-event printouts with a time resolution of 1 millisecond, remote oscillography, line fault location, and transformer load monitoring. In addition, digital computation capability makes adaptive protective functions possible—ensuring optimal protective relaying with changing power system conditions.

A users group of representatives of the utilities involved, suppliers, EPRI, and ESEERCO has been formed and is meeting three times a year to document operating experience. Standardized reporting forms are being used to register responses to power system disturbances and to accumulate meaningful reliability data. A final report on operating experience is planned for late 1990.

Control and Information Systems

Expert Systems for Combustion Turbines

by George Quentin, Generation and Storage Division

ABSTRACT *Troubleshooting combustion turbine problems usually requires an experienced technician, but experts are not always available when turbines fail to start. This is a particular problem for electric utilities, which use combustion turbines largely as on-demand peaking units. EPRI is developing expert systems to diagnose the problems and return combustion turbines to service as quickly as possible, and has built a portable user interface called SA•VANT to take the systems into the field. Expert systems under development include startup advisors for Westinghouse Model 501 and TurboPower and Marine Model FT4 combustion turbine generators.*

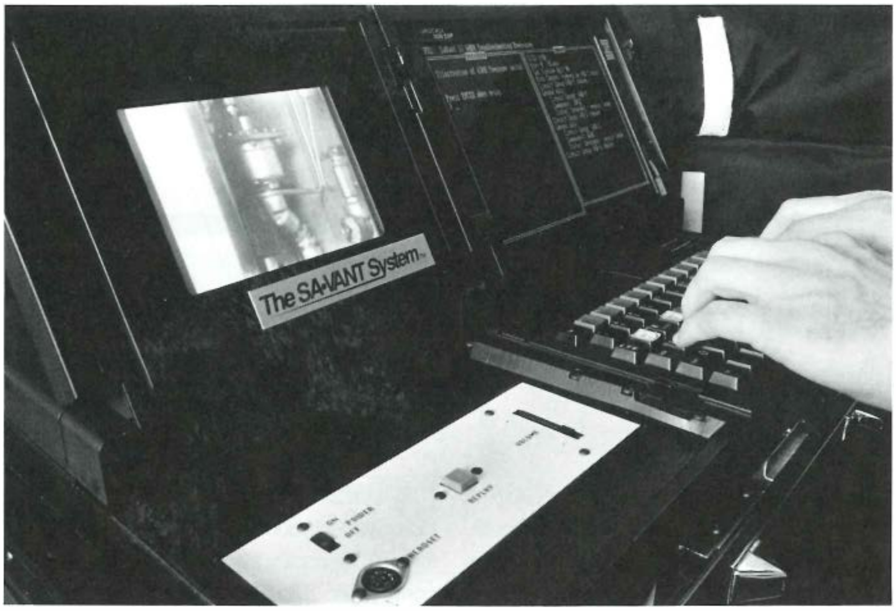
Electric utilities typically use combustion turbines as peaking units, relying on them to generate power for brief, infrequent periods. When a turbine fails to start on demand, experienced technicians must be called in to troubleshoot the problem and get the turbine operating as soon as possible. Often experts are not readily available, and the utility must resort to costly power purchases to supply necessary service to customers. To provide expert support and training for less-experienced plant personnel, EPRI is developing diagnostic expert system startup advisors.

SA•VANT: the user interface

An essential step in implementing expert systems was the development of a portable user interface that could take the systems wherever they were needed. Under EPRI contract, Honeywell created SA•VANT™ to meet this crucial need (RP2562). SA•VANT is a rugged user interface unit that travels inside a convenient suitcase to field locations, such as combustion turbine control cabs. The unit, shown in Figure 1, includes a state-of-the-art microcomputer; dual-screen, flat-panel video displays for text and graphics; a keyboard; a 2-inch, 30-column printer; and a voice input and output system. Users can enter commands on a keypad or use the voice system. Output is provided to the user as text, interactive video, graphics, speech, and/or hard copy. SA•VANT can display both schematic diagrams and video images of equipment. Expert systems software resides on optical disks that can be easily inserted and removed. With proper software, SA•VANT not only can provide expert advice and guidance in the field but also can support in-field instruction, as well as interface with field equipment for on-line data acquisition and analysis.

To evaluate the effectiveness of SA•VANT, Honeywell produced a modest expert system for troubleshooting one problem common to combustion turbines: control system ground faults. This system is called GFAX (Ground Fault Advisor Expert System). During 1988 trials at Jersey Central Power & Light's Gilbert station, technicians with little experience were able to detect ground faults independently in

Figure 1 SA•VANT is a portable user interface developed by EPRI to take combustion turbine expert systems into the field. The rugged unit travels to plant sites in a suitcase that houses its microcomputer, text and graphics video displays, keyboard, and printer.



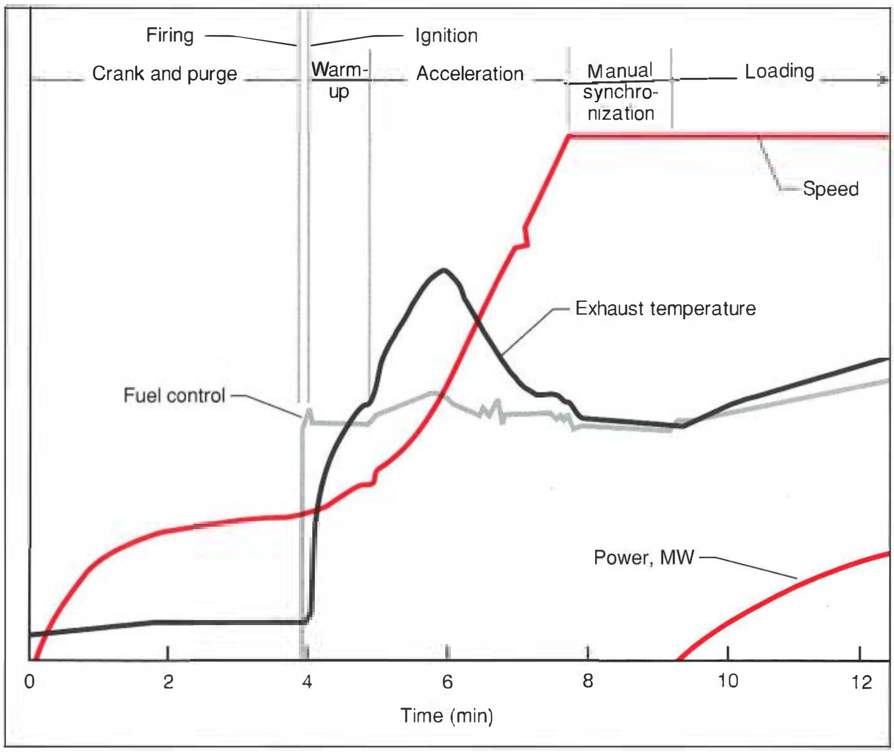


Figure 2 The new prototype of WESAX (Westinghouse Startup Advisor Expert System) will compare on-line startup data with these normal startup curves. By rapidly noting departures from normal, WESAX will make it possible to diagnose aborted gas turbine startups immediately.

an average of 26 minutes after only one hour of training on SA•VANT and GFAX. These technicians indicated that they would have been unable to isolate the faults without GFAX. GFAX also made it possible for experienced technicians to reduce their diagnosis time from 60 minutes to 25 minutes.

Turbine startup advisors

Convinced that expert systems could be applied to combustion turbine problems, EPRI began to develop broadly based startup advisor expert systems for utility combustion turbine models. The models selected for attention were the Westinghouse 501, the Turbo-Power and Marine FT4, and the General Electric MS7001.

To date, the most progress has been made with Honeywell's WESAX (Westinghouse Start-up Advisor Expert System), through RP3031. Honeywell began by constructing a logic framework for a startup advisor system and then spent over six weeks interviewing nine turbine startup experts—two system design engineers, three consulting engineers, and four power plant supervisors/engineers—to collect relevant information and experience. Honeywell assembled the collected information into WESAX's extensive knowledge base. The system took two years to develop.

At Jersey Central's Sayreville station, field tests are under way on a WESAX prototype that was developed in the first phase of the project. Another round of field tests will begin at Carolina Power & Light's Darlington plant in mid-1990. All field tests will be analyzed by ARINC Research to determine the degree of startup reliability improvement achieved by WESAX. Data entry to these prototypes is mostly manual: data are supplied by the operator rather than by means of automatic, on-line data entry.

For the second phase of WESAX development, Honeywell is creating a more sophisticated version that can receive on-line data input from combustion turbine control systems. This expert system compares startup data with normal startup curves showing speed, temperature, power, and other critical transient data (Figure 2). SA•VANT will apply the expert system, receiving input from advanced turbine controls, such as the Westinghouse Distributed Process Family (WDPF) controls or the TRISEN control system. Field tests are being planned at Nevada Power's Clark station (WDPF) and at Georgia Power's Wilson station (TRISEN).

Meanwhile, Honeywell is proceeding with the development of a startup advisor expert system for the Model FT4 combustion turbines manufactured by the TurboPower and Marine Division of United Technologies (RP3031). This system is called UTSAX (UTC Startup Advisor Expert System). Honeywell is collecting information for the UTSAX knowledge base from turbine troubleshooters at Consolidated Edison of New York, Northeast Utilities, and New Jersey's Public Service Electric & Gas. All three utilities are project cofunders and will serve as field test hosts. Field tests are planned to begin in late 1990.

EPRI plans to eventually develop a startup advisor for General Electric Model MS7001 turbines as well. This particular system will be called GESAX (General Electric Startup Advisor Expert System). Funding may be available to begin development in 1991.

Exploring other uses and commercialization

The expert systems described thus far are all startup advisors, but expert systems can answer many other utility needs. Southwestern Research Institute recently completed an EPRI study (RP2953) that indicated that such systems might be used as combustion turbine vibration and balancing advisors. Southwestern is collecting utility field data on Westinghouse Model 501 combustion turbines to develop a simple vibration and balancing expert system that can be used with SA•VANT. Because the knowledge base for each expert system resides on a removable optical disk, it is easy to use one SA•VANT user interface for different applications. EPRI is also beginning to explore the possibility of developing a borescoping advisor and a combustor inspection advisor for use with SA•VANT. Future expert systems applications might also include a combustion turbine maintenance planning advisor and a life management advisor based on a visual database of blade and vane failures.

While the development of expert systems moves forward, EPRI is evaluating the possibility of commercializing SA•VANT and its associated expert systems. (SA•VANT field test units are currently assembled and serviced by Sonoma Computer Integrators, Sonoma, California.) SA•VANT can be used for expert systems applications at all kinds of power plants, so commercialization is likely in the not-too-distant future. Commercialized SA•VANT units will offer utilities enhanced visual displays that feature digital interactive video (DVI). In addition, the commercialized units will offer high reliability coupled with reduced unit weight, smaller power requirements, and lower cost.

New Contracts

Project	Funding/ Duration	Contractor/EPRI Project Manager
Business Management		
Potential Demand for Increased Use of Gas in Power Generation (RP2369-44)	$50,000 4 months	Edison Electric Institute/ *H. Mueller*
Customer Systems		
DSManager Support (RP1485-14)	$60,000 13 months	Electric Power Software Center/*P. Hanser*
ETS Users Group Meeting and Exposition (RP2731-11)	$124,600 12 months	Policy Research Associates, Inc./ *J. Kesselring*
Heat Recovery With Ice Storage Systems (RP2732-33)	$92,300 24 months	Colorado State University/ *R. Wendland*
Technical Support for Microwave and Radio-Frequency Electrotechnologies in Process Industries (RP2783-20)	$50,900 12 months	Thermo Energy Corp./ *A. Amarnath*
Model All-Electric Restaurant Demonstration Project (RP2890-16)	$300,100 26 months	Architectural Energy Corp./*K. Johnson*
Nonazeotropic Water-Cooled Chiller (RP2891-10)	$130,300 12 months	Trane Co./*P. Joyner*
Scoping Study on Advanced Educational Services (RP2935-9)	$68,500 4 months	Spacebridge Broadcasting Co./*M. Samotyj*
Commercial Water-Heating Applications Handbook (RP3169-1)	$192,000 27 months	D. W. Abrams, PE & Associates/*K. Johnson*
Electrical Systems		
Diagnostics for Detecting and Measuring Water Tree Charge Motion in Polymers (RP2957-3)	$195,700 22 months	University of Tennessee/ *T. Rodenbaugh*
Mitigation of Water Treeing (RP2957-4)	$320,000 16 months	Ontario Hydro/ *T. Rodenbaugh*
Development of Advanced Static VAR Compensator (RP3023-1)	$446,300 6 months	Westinghouse Electric Corp./*H. Mehta*
Longitudinal NDE of New Wood Utility Poles (RP3078-1)	$791,300 26 months	Engineering Data Management, Inc./*H. Ng*
Assessment of Distribution System Power Quality (RP3098-1)	$2,355,200 46 months	Electrotek Concepts, Inc./ *G. Rauch*
Simultaneous Power Transfer Capability Evaluation Project: Direction for Software Development (RP3140-1)	$75,200 13 months	Union Electric Co./ *M. Lauby*
Bulk Transmission System Reliability Evaluation for Large-Scale Systems, Phase 3: Production-Grade Code (RP3159-1)	$687,700 18 months	Public Service Electric & Gas Co./*M. Lauby*
Development and Incorporation of Models for Flexible AC Transmission Systems (RP4000-11)	$103,400 6 months	Ontario Hydro/*M. Lauby*
Environment		
Economic Analysis of Emerging Environmental Issues (RP1742-9)	$85,600 11 months	Resources for the Future, Inc./*V. Niemeyer*
Evaluation of Surface Water Chemistry and Fish Communities in Adirondack Lakes (RP2174-16)	$200,000 12 months	Empire State Electric Energy Research Corp./ *J. Huckabee*
FASTCHEM™: Verification, Application, and Sensitivity Analysis (RP2485-19)	$333,900 17 months	Lawrence Berkeley Laboratory/*D. McIntosh*
Integrated Forest Study on Effects of Atmospheric Deposition (RP2621-3)	$94,700 12 months	Desert Research Institute/ *L. Pitelka*
Susceptibility of North American Flora to Global Climate Change (RP3041-3)	$140,000 26 months	The Nature Conservancy/ *L. Pitelka*
Exploratory Research		
Improved Superclean CrMoV Steel (RP2741-6)	$131,400 23 months	Japan Steel Works America, Inc./*R. Jaffee*
Bifurcation and Chaos in Power Systems (RP8010-8)	$120,000 19 months	University of California, Berkeley/*M. Lauby*
Generation and Storage		
Assessment and Transfer of EPRI Technologies to Public Service of Indiana (RP982-46)	$73,500 6 months	Encor-America, Inc./ *T. Morasky*
On-Line Monitoring of High Temperature (RP1403-48)	$70,500 11 months	CAPCIS March, Ltd./ *W. Bakker*
Scoping Study of Utility Power Plant Audits (RP1403-49)	$49,500 4 months	Encor-America, Inc./ *G. Poe*
Recovery of Methanol From a Catalyst Slurry by a Pervaporation Membrane Separation Technique (RP2146-7)	$53,400 9 months	University of Cincinnati/ *S. Yunker*
Waste-to-Energy Screening and Permitting Guide (RP2190-5)	$717,200 8 months	Bechtel Group, Inc./ *E. Hughes*
Condenser Microbiofouling Control Handbook (RP2300-16)	$135,600 13 months	Crescent Project Management/ *W. Micheletti*
Intelligent Decision Systems for Utility Applications: Feasibility Study (RP2308-19)	$90,600 9 months	Strategic Decisions Group/*M. Divakaruni*
Calcium-Based Ash Deposition in Utility Boilers (RP2425-8)	$60,000 20 months	University of North Dakota/*A. Mehta*
TVA Demonstration Site Support (RP2543-13)	$84,300 12 months	Fluor Daniel/ *J. Fishbaugher*
Nuclear Power		
Modular High-Temperature Gas Reactor Evaluation (RP2079-27)	$80,000 8 months	Duke Engineering & Services, Inc./*E. Rodwell*
ACE/MACE Research Cofunding (RP2802-81)	$90,000 14 months	Siemens/*F. Rahn*
Conceptual Design for an On-Site Spent-Fuel Transfer System (RP2813-25)	$113,200 9 months	Transnuclear, Inc./ *R. Lambert*
Infrared Thermography: Predictive Maintenance Guidelines (RP2814-18)	$67,100 6 months	American Risk Management/*G. Allen*
High-Level-Waste Technical Support (RP3055-8)	$80,000 7 months	Analytic Sciences Corp./ *R. Shaw*
Diagnostic Tool for Operator Training (RP3082-1)	$243,000 15 months	Accident Prevention Group, Inc./*A. Singh*
Concrete Structure Seismic Response (RP3094-1)	$241,000 17 months	Sozen & Moehle/*H. Tang*
Expert System for Snubber Reduction/ Piping Design Improvement (RP3095-1)	$159,200 15 months	Impell Corp./*H. Tang*
Development of Seismic Instrumentation Guidelines for Nuclear Power Plant Application (RP3096-1)	$103,900 7 months	Yankee Atomic Electric Co./*J. Schneider*
Knowledge Based Technology Applications Center: Technical Support (RP3109-2)	$79,200 12 months	S. Levy, Inc./*B. Sun*
Maintenance Personnel Productivity Improvement (RP3111-2)	$223,800 10 months	Westinghouse Electric Corp./*J. O'Brien*

New Technical Reports

Requests for copies of reports should be directed to Research Reports Center, P.O. Box 50490, Palo Alto, California 94303; (415) 965-4081. There is no charge for reports requested by EPRI member utilities, U.S. universities, or government agencies. Reports will be provided to nonmember U.S. utilities only upon purchase of a license, the price for which will be equal to the price of EPRI membership. Others in the United States, Mexico, and Canada pay the listed price. Overseas price is double the listed price. Research Reports Center will send a catalog of EPRI reports on request. To order one-page summaries of reports, call the EPRI Hotline, (415) 855-2411.

CUSTOMER SYSTEMS

Foodservice Sourcebook: A Quick-Reference Guide to Industry Information and Sources, Revision 1
EM-6135 (Rev. 1) Final Report (RP2890-5); $100
Contractor: W. I. Whiddon & Associates, Inc.
EPRI Project Manager: K. Johnson

Supplemental Photosynthetic Lighting for Greenhouse Tomato Production
CU-6562 Final Report (RP2285-9); $100
Contractor: Public Service Electric & Gas Co.
EPRI Project Manager: K. Johnson

Case Studies Using WENS–PC and FORECAST MASTER PLUS
CU-6604 Final Report (RP2279-2); $32.50
Contractor: Pacific Consulting Services
EPRI Project Managers: R. Squitieri, P. Cleary

The Performance Potential of Local and Distributed Load Controllers
CU-6632 Final Report (RP1940-14); $100
Contractors: Analysis and Control of Energy Systems, Inc.; BRI Systems, Inc.
EPRI Project Manager: L. Carmichael

Expected Energy Use of Ice Storage and Cold Air Distribution Systems in Large Commercial Buildings
CU-6643 Final Report (RP2732-16); $100
Contractor: Purdue University
EPRI Project Manager: R. Wendland

Development and Application of a Uniform Testing Procedure for Griddles
CU-6686 Final Report (RP2890-3); $100
Contractor: Pacific Gas and Electric Co.
EPRI Project Manager: K. Johnson

Detailed Field Evaluation of a Cold Air Distribution System, Vols. 1 and 2
CU-6690 Final Report (RP2732-3); Vol. 1, $100; Vol. 2, $100
Contractor: Dorgan Associates, Inc.
EPRI Project Manager: R. Wendland

The Model Electric Restaurant, Vol. 1: Restaurant Subsystem Analysis and Evaluation
CU-6702 Final Report (RP2890-4); $100
Contractors: Architectural Energy Corp.; Pennsylvania State University
EPRI Project Manager: K. Johnson

Pilot Study of Commercial Water-Loop Heat Pump Compressor Life
CU-6739 Final Report (RP2480-6); $100
Contractor: Policy Research Associates, Inc.
EPRI Project Managers: M. Blatt, M. Khattar

Electric Thermal Storage Applications Guide and Product Directory
CU-6741 Final Report (RP2731-5); $100
Contractor: George Reeves Associates, Inc.
EPRI Project Manager: V. Rabl

Efficient Electricity Use: Estimates of Maximum Energy Savings
CU-6746 Final Report (RP2788); $100
Contractor: Barakat & Chamberlin, Inc.
EPRI Project Manager: T. Yau

ELECTRICAL SYSTEMS

Factory Evaluation of a Laser Instrument for Cable Inspection
EL-6412 Final Report (RP794-5); $25
Contractor: Cablec Corp.
EPRI Project Manager: J. Porter

Control Center Survey: Installed and Planned Applications Software
EL-6634 Final Report (RP2473-32); $25
Contractor: Clauder Systems Research, Inc.
EPRI Project Manager: D. Curtice

GENERATION AND STORAGE

Time-Domain Reflectometry for Monitoring Cable Changes: Feasibility Study
GS-6642 Final Report (RP2308-18); $25
Contractor: Purdue University
EPRI Project Manager: J. Stein

1988 Conference on Power Plant Simulators and Modeling
GS/NP-6670 Proceedings (RP1184-28); $350
Contractor: TRAX Corp.
EPRI Project Managers: M. Divakaruni, J. Sursock

Simulator-Based Training and Technology Transfer for Fossil Plants: An R&D Plan and Technology Assessment
GS-6672 Final Report (RP2819-6); $250
Contractors: General Physics Corp.; TRAX Corp.; Science Applications International Corp.
EPRI Project Manager: M. Divakaruni

R&D Plans for Advanced Computer and Control Technologies, Vol. 1: Executive Summary
GS-6673 Final Report (RP2819-5); $100
Contractor: Sargent & Lundy
EPRI Project Manager: M. Divakaruni

R&D Plans for Advanced Computer and Control Technologies, Vol. 2: Instrumentation and Control Systems
GS-6673 Final Report (RP2710-2); $250
Contractors: Bailey Controls Co.; Science Applications International Corp.
EPRI Project Manager: M. Divakaruni

R&D Plans for Advanced Computer and Control Technologies, Vol. 3: Expert-Systems Technology Assessment
GS-6673 Final Report (RP2923-2); $250
Contractors: Expert-Ease Systems, Inc.; Sargent & Lundy; Science Applications International Corp.
EPRI Project Manager: M. Divakaruni

R&D Plans for Advanced Computer and Control Technologies, Vol. 4: Process Integration and Information Systems for Fossil Plant Automation—Technology Assessment
GS-6673 Final Report (RP2819-3); $250
Contractors: Systems Control, Power Automation Inc.; Science Applications International Corp.
EPRI Project Manager: M. Divakaruni

Compressed-Air Energy Storage: Pittsfield Aquifer Field Test, Test Data—Engineering Analysis and Evaluation
GS-6688 Final Report (RP2488-10); $47.50
Contractor: ANR Storage Co.
EPRI Project Manager: B. Mehta

An Investigation of Precipitator Wide Plate Spacing
GS-6711 Final Report (RP1835-5); $40
Contractor: Combustion Engineering, Inc.
EPRI Project Manager: R. Altman

Fish Protection Systems for Hydro Plants
GS-6712 Interim Report (RP2694-1); $47.50
Contractor: Stone & Webster Engineering Corp.
EPRI Project Managers: C. Sullivan, J. Mattice, J. Berning

Coke Formation Index: A Measure of Particulate Formation in Oil Combustion
GS-6714 Topical Report (RP2869-4, RP2778-7); $32.50
Contractors: Electric Power Technologies, Inc.; Princeton University
EPRI Project Managers: D. Eskinazi, W. Rovesti

Sodium/Sulfur Battery: Supporting R&D on Sulfur-Side Components
GS-6718 Final Report (RP128-11); $40
Contractor: SRI International
EPRI Project Manager: R. Weaver

Fossil Plant Retrofits for Improved Heat Rate and Availability
GS-6725 Proceedings; $500
EPRI Project Manager: G. Touchton

Workshop on Materials Issues in Circulating Fluidized-Bed Combustors
GS-6747 Proceedings (RP979-25); $77.50
EPRI Project Manager: J. Stallings

Copper Oxychloride as a Fireside Additive in Coal-Fired Utility Boilers
GS-6751 Final Report (RP1839-4); $32.50
Contractor: Battelle, Columbus Division
EPRI Project Manager: A. Mehta

Assessment of Asbestos Insulation Substitutes
GS-6752 Final Report (RP1266-50); $500
Contractor: University of Tennessee at Chattanooga
EPRI Project Manager: J. Tsou

GADSRAM User's Manual: Version 2.0
GS-6776 Final Report (RP2921-4); $32.50
Contractor: ARINC Research Corp.
EPRI Project Manager: J. Weiss

NUCLEAR POWER

Evaluation of Discrepancies in Assembly Cross-Section Generator Codes, Vol. 3: Assembly Calculations
NP-6147 Final Report (RP2803-2); $25
Contractor: Utility Resource Associates
EPRI Project Manager: R. Breen

Utility Industry Evaluation of the Sodium Advanced Fast Reactor
NP-6633 Final Report (RP3030); $32.50
EPRI Project Manager: E. Rodwell

Utility Industry Evaluation of the Power Reactor Inherently Safe Module
NP-6644 Final Report (RP3030); $32.50
EPRI Project Manager: E. Rodwell

Utility Industry Evaluation of the Metal Fuel Facility and Metal Fuel Performance for Liquid Metal Reactors
NP-6647 Final Report (RP3030); $25
EPRI Project Manager: E. Rodwell

STARRS–MMS Code: Evaluating Steam Generator Tube Ruptures, Vols. 2–4
NP-6668 Final Report (RP2453-4); Vol. 2, $25; Vol. 3, $25; Vol. 4, $32.50
Contractor: Science Applications International Corp.
EPRI Project Manager: S. Kalra

Fuel Consolidation Demonstration: Consolidation Concept Development
NP-6722 Interim Report (RP2240-2); $32.50
Contractor: Northeast Utilities Service Co.
EPRI Project Manager: R. Lambert

Control-Room Operator Alertness and Performance in Nuclear Power Plants
NP-6748 Final Report (RP2184-7); $40
Contractor: Circadian Technologies, Inc.
EPRI Project Manager: J. O'Brien

Investigation of In-Leakage and Fuel Corrosion in Certain BWRs
NP-6779-M Final Report (RP2946-3); $25
Contractor: S. Levy, Inc.
EPRI Project Manager: R. Yang

CALENDAR

For additional information on the meetings listed below, please contact the person indicated.

JULY

10–12
Workshop: Steam Generator Repair and Replacement
Denver, Colorado
Contact: Chuck Welty, (415) 855-2783

16–17
RCM Users Group Meeting
Location to be determined
Contact: Gordon Allen, (415) 855-2219

24–26
Slagging Combustion Interest Group Meeting
Edmonton, Canada
Contact: Angelos Kokkinos, (415) 855-2494

24–26
Steam Generator Nondestructive Evaluation
Mystic, Connecticut
Contact: Chuck Welty, (415) 855-2783

24–27
Advanced Machinery Vibration Diagnostics
Eddystone, Pennsylvania
Contact: Sam Haddad, (415) 855-2172

29–August 3
5th International Conference: Indoor Air Quality and Climate
Toronto, Canada
Contact: Ron Wyzga, (415) 855-2577

31–August 1
Workshop: Digital Signal Processing for NDE and Plant Maintenance
Charlotte, North Carolina
Contact: Jim Lang, (415) 855-2038, or Ramesh Shankar, (704) 547-6127

AUGUST

7–10
Power Plant Life Assessment and Stress Monitoring
Eddystone, Pennsylvania
Contact: Steve Gehl, (415) 855-2770, or Vis Viswanathan, (415) 855-2450

20–23
Power Plant Valve Symposium
Charlotte, North Carolina
Contact: Jim Lang, (415) 855-2038

28–30
Generator Diagnostics
Eddystone, Pennsylvania
Contact: Murthy Divakaruni, (415) 855-2409

28–30
International Conference: Measuring Waterborne Trace Substances
Baltimore, Maryland
Contact: Winston Chow, (415) 855-2868

SEPTEMBER

5–6
Workshop: Modeling Ground Motion Close to Large Earthquakes
Palo Alto, California
Contact: John Schneider, (415) 855-7921

10–14
Seminar: PCB/Dioxin 1990
Bayreuth, Germany
Contact: Gil Addis, (415) 855-2286

17–19
Seminar: Service Water Systems Reliability Improvement
Atlanta, Georgia
Contact: Norris Hirota, (415) 855-2084

18–20
Conference: Condenser Technology
Boston, Massachusetts
Contact: John Tsou, (415) 855-2220

18–21
Machinery Balancing and Alignment
Charlotte, North Carolina
Contact: Tom McCloskey, (415) 855-2655

19–21
Effects of Coal Quality on Power Plants
St. Louis, Missouri
Contact: Arun Mehta, (415) 855-2895

24–26
Railroad, Pipeline, and Transmission Line Compatibility
Haslet, Texas
Contact: Jim Hall, (415) 855-2305

25–27
Diesel Generator Diagnostics
Charlotte, North Carolina
Contact: Sam Haddad, (415) 855-2172

25–27
Use of Less-Volatile Amines in PWR Secondary-Side Water Treatment
Tampa, Florida
Contact: Tom Passell, (415) 855-2070

26–28
Coal Cleaning Plant O&M
Homer City, Pennsylvania
Contact: Barbara Fyock, (412) 479-6015

27–28
Overhead Transmission Line Optimization: TLOPWT
Haslet, Texas
Contact: Dick Kennon, (415) 855-3211

OCTOBER

1–5
Computer-Aided Control System Analysis
Birmingham, Alabama
Contact: Murthy Divakaruni, (415) 855-2409

2–4
Electric Motor Diagnostics
Eddystone, Pennsylvania
Contact: Jim Edmonds or J C. White, (415) 855-2291

9–11
Noncombustion Waste
New Orleans, Louisiana
Contact: Mary McLearn, (415) 855-2487

10–11
Workshop: Feedwater Heater Maintenance Technology
Eddystone, Pennsylvania
Contact: John Tsou, (415) 855-2220

15–17
Incipient Failure Detection: Predictive Maintenance for the 1990s
Philadelphia, Pennsylvania
Contact: Sam Haddad, (415) 855-2172, or John Scheibel, (415) 855-2850

15–17
Information Technology for the Power Industry: CD ROM and Laser Disks for PCs
Washington, D.C.
Contact: Joe Judy, (415) 855-8936

16–18
Fuel Supply Seminar
Memphis, Tennessee
Contact: Howard Mueller, (415) 855-2745

17–19
AIRPOL/90 Seminar: Solving Corrosion Problems in Air Pollution Control Equipment
Louisville, Kentucky
Contact: Paul Radcliffe, (415) 855-2720

23–24
Thermography
Location to be determined
Contact: Gordon Allen, (415) 855-2219, or Mike Downs, (415) 855-7940

30–November 2
Vibration Testing and Analysis
Eddystone, Pennsylvania
Contact: Sam Haddad, (415) 855-2172

31–November 1
1990 Fuel Oil Utilization Workshop
Washington, D.C.
Contact: William Rovesti, (415) 855-2519

NOVEMBER

1–2
T&D Cable Installation
St. Petersburg, Florida
Contact: Tom Rodenbaugh, (415) 855-2306

5–9
Fireside Performance of Coal-Fired Boilers
Eddystone, Pennsylvania
Contact: Bob Leyse, (415) 855-2995

12–14
Main Coolant Pump Monitoring and Diagnostics
Eddystone, Pennsylvania
Contact: Joe Weiss, (415) 855-2751

14–16
1990 Electric Utility Market Research Symposium
Atlanta, Georgia
Contact: Thom Henneberger, (415) 855-2885

27–29
Fossil Power Plant Cycling
Washington, D.C.
Contact: James Valverde, (415) 855-7998

28–29
NSAC and Operational Reactor Safety Engineering and Review Group Workshop: Self-Assessment During Plant Shutdown
Seattle, Washington
Contact: Bill Reuland, (415) 855-2977

DECEMBER

3–5
Symposium: Macrofouling
Orlando, Florida
Contact: Norris Hirota, (415) 855-2084

4–5
Air-Operated-Valve Diagnostics
Eddystone, Pennsylvania
Contact: Joe Weiss, (415) 855-2751

4–6
Fossil Fuel Plant Cycling
Washington, D.C.
Contact: Maureen Barbeau, (415) 855-1080

5–7
Workshop: Applications of Chaos
San Francisco, California
Contact: Jong Kim, (415) 855-2671

12–14
Workshop: Fossil Fuel Plant Control and Automation
Phoenix, Arizona
Contact: Murthy Divakaruni, (415) 855-2409

Authors and Articles


Peck


Hakkarinen


Levin


Pitelka


DeMeo


Schaefer


Curtice


Balu

Sharper Focus on Greenhouse Science (page 4) was written by John Douglas, science writer, with technical assistance from three staff members of EPRI's Environment Division.

Stephen Peck, director of the division since January 1989, joined EPRI in 1976. He became a program manager in 1979, the technical director for integrating environmental and economic studies in 1982, and a department director in 1986. Peck was formerly on the economics faculty of the University of California at Berkeley.

Chuck Hakkarinen, named technical manager in the Atmospheric Sciences Program in 1989, was formerly manager of environmental data analysis. He came to EPRI in 1974 as a project manager for environmental assessment and later (1979–1984) was technical assistant to the division director.

Leonard Levin is a project manager in the Environmental Risk Analysis Program. He came to EPRI in 1986 after six years as a senior scientist and meteorologist at Woodward-Clyde Consultants. Before that, he worked successively as a senior scientist at Science Applications International and as the director of physical sciences programs for EA Engineering, Science, and Technology.

Louis Pitelka joined EPRI's Ecological Studies Program in 1984, taking responsibility for research projects involving plant ecology. Previously, he was with the National Science Foundation, where he directed a program in population biology and physiological ecology, and at Bates College, where he was on the biology faculty for nine years and served as department chairman. ■

Excellent Forecast for Wind (page 14) was written by Taylor Moore, the *Journal*'s senior feature writer, in cooperation with two research managers of EPRI's Generation and Storage Division.

Edgar DeMeo, manager of the Solar Power Program since 1980, guides research primarily in photovoltaics and wind energy technologies. He came to the Institute in 1976 after six years on the engineering research faculty at Brown University and two years as an instructor at Annapolis.

John Schaefer manages field test projects for solar and wind technologies. He came to EPRI in 1985 after nine years as a consultant on the planning and costing of electric power systems. In the 1960s and 1970s, he held teaching posts at California State University (San Jose), Stanford, and the University of El Salvador and worked as a design engineer for nuclear, electrical, and electronic systems. ■

Simulating the Control Center (page 26) was written by David Boutacoff, *Journal* feature writer, who drew background material from two research managers of EPRI's Electrical Systems Division.

David Curtice has been with EPRI's Power System Planning and Operations Program since August 1987. He is a project manager with a special interest in system operations. Before joining EPRI, he worked for 11 years at Systems Control, where he was involved in the development of energy management systems and application software.

Neal Balu, manager of the Power System Planning and Operations Program since early 1988, came to EPRI as a project manager in 1979. He had previously worked for seven years in the system planning department of Southern Company Services, heading the systems dynamics section. Earlier, he spent four years on the faculty of the Indian Institute of Technology in Bombay. ■

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